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Technical Report

Reconnaissance of Background Infrasound at Selected Future IMS Locations, Atlantic Ocean

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13. ABSTRACT (*Maximum 200 words*)

This contract yielded infrasonic reconnaissance at several sites that have been selected for installation of infrasonic arrays as part of the International Monitoring System (IMS). Specifically, we have installed temporary stations at three islands in the Atlantic Ocean. The primary goal was to broadly characterize the variability of the natural background infrasound on these in a way that could be helpful the deployers of the future monitoring facilities. These islands each offer a variety of environmental settings and are inherently different from each other in terms of natural characteristics such as size, shape, wind, weather, topography, and vegetation. As a result, this study has also provided insight about parameters that affect the quality of infrasonic measurements on relatively small islands. We have assessed the utility of infrasonic monitoring stations on these island s and have found suitable locations for all array elements. The locations are Ascension Island, Sao Miguel Island, Azores and Maio Island, Republic of Cape Verde. This report separates results from each island chapter. Each chapter begins with a detailed executive summary of each survey.

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PREFACE

The assistance provided by Panduronga Dessai and his colleagues at the Instituto de Meteorologia, Portugal in Ponta Delgada, Azores is greatly appreciated. Panduronga Dessai's involvement spanned all phases of the Azores survey. We were assisted by numerous people in Cape Verde. We wish to express our sincere appreciation to António Joaquim R. M. Fernandes, Cape Verde's minister of infrastructure and housing), Dr João Fonseca, Manuel Ribeiro (the mayor of Maio), Arlindo do Rosario, Flavio Silva, and Ana Margarida Martins for the assistance they provided us before, during, and after the survey in Cape Verde. Iain Atkinson (Merlin Communications) provided us with information on the power lines in the area and the logistics of deploying hardware on Ascension island. Valuable assistance was provided by two Administrators of Ascension Island - Roger Huxley and Geoffrey Fairhurst. The staff at IGPP's North lab provided technical assistance. Dick Kromer tested the responses of the MB2000's. Ruedi Widmer (IGPP) provided the poles and zeros for the MB2000's.

CONVERSION TABLE

Conversion Factors for U.S. Customary to metric (SI) units of measurement.

MULTIPLY → BY → TO GET

TO GET ← BY ← DIVIDE

angstrom	1.000 000 x E -10	meters (m)
atmosphere (normal)	1.013 25 x E +2	kilo pascal (kPa)
bar	1.000 000 x E +2	kilo pascal (kPa)
barn	1.000 000 x E -28	meter^2 (m^2)
British thermal unit (thermochemical)	1.054 350 x E +3	joule (J)
calorie (thermochemical)	4.184 000	joule (J)
cal (thermochemical/cm^2)	4.184 000 x E -2	mega joule/m^2 (MJ/m^2)
curie	3.700 000 x E +1	*giga bacquerel (GBq)
degree (angle)	1.745 329 x E -2	radian (rad)
degree Fahrenheit	$t_k = (t^o f + 459.67)/1.8$	degree kelvin (K)
electron volt	1.602 19 x E -19	joule (J)
erg	1.000 000 x E -7	joule (J)
erg/second	1.000 000 x E -7	watt (W)
foot	3.048 000 x E -1	meter (m)
foot-pound-force	1.355 818	joule (J)
gallon (U.S. liquid)	3.785 412 x E -3	meter^3 (m^3)
inch	2.540 000 x E -2	meter (m)
jerk	1.000 000 x E +9	joule (J)
joule/kilogram (J/kg) radiation dose absorbed	1.000 000	Gray (Gy)
kilotons	4.183	terajoules
kip (1000 lbf)	4.448 222 x E +3	newton (N)
kip/inch^2 (ksi)	6.894 757 x E +3	kilo pascal (kPa)
ktap	1.000 000 x E +2	newton-second/m^2 (N-s/m^2)
micron	1.000 000 x E -6	meter (m)
mil	2.540 000 x E -5	meter (m)
mile (international)	1.609 344 x E +3	meter (m)
ounce	2.834 952 x E -2	kilogram (kg)
pound-force (lbs avoirdupois)	4.448 222	newton (N)
pound-force inch	1.129 848 x E -1	newton-meter (N-m)
pound-force/inch	1.751 268 x E +2	newton/meter (N/m)
pound-force/foot^2	4.788 026 x E -2	kilo pascal (kPa)
pound-force/inch^2 (psi)	6.894 757	kilo pascal (kPa)
pound-mass (lbm avoirdupois)	4.535 924 x E -1	kilogram (kg)
pound-mass-foot^2 (moment of inertia)	4.214 011 x E -2	kilogram-meter^2 (kg-m^2)
pound-mass/foot^3	1.601 846 x E +1	kilogram-meter^3 (kg/m^3)
rad (radiation dose absorbed)	1.000 000 x E -2	**Gray (Gy)
roentgen	2.579 760 x E -4	coulomb/kilogram (C/kg)
shake	1.000 000 x E -8	second (s)
slug	1.459 390 x E +1	kilogram (kg)
torr (mm Hg, 0^0 C)	1.333 22 x E -1	kilo pascal (kPa)

*The bacquerel (Bq) is the SI unit of radioactivity; 1 Bq = 1 event/s.
**The Gray (GY) is the SI unit of absorbed radiation.

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SECTION 1
THE INFRASOUND SITE SURVEY CONDUCTED IN THE AZORES, PORTUGAL

This section reviews the results of an infrasound survey that was conducted in the Azores near the International Monitoring System (IMS) nominal infrasound site IS42. This survey was conducted by researchers at the University of California, San Diego to find the location near the nominal site coordinates that would provide the best overall conditions for detecting infrasonic signals of interest above noise and for locating and characterizing the sources. The report summarizes the main elements of the survey - the site selection, the survey, the analysis of the infrasonic noise and meteorological data and our recommendations for the location, configuration, operation and maintenance of the permanent IMS infrasound array.

Following the requirements for a standard survey as outlined by the Provisional Technical Secretariat (PTS), we conducted the survey of infrasonic noise and meteorological conditions at four points. The sites were chosen after considering meteorological data, topography, vegetation and logistics on all islands in the Azores. The review clearly indicated that the main island in the Azores, Sao Miguel, provides the best overall conditions for establishing an infrasound array in this region. The four sites we selected on Sao Miguel sample diverse means of reducing wind and infrasonic noise. One station was placed in a large calderra. Two other stations were located in dense Criptomeria forests. The fourth site was located on a broad plateau near the eastern end of the island. During a three-week period in November and December of 1998, infrasonic noise and wind speed, direction, air temperature and humidity data were recorded simultaneously at these sites. Pressure data were collected using the MB2000 microbarometer.

We analyzed the meteorological and pressure data to characterize the dependence of infrasonic noise on location and on time. Power spectral density was estimated using Welch's method. This analysis indicates that the most suitable location for an IMS array in the Azores is at the eastern site on Sao Miguel, Cha das Mulas. This area has little topography and is sparsely populated. The area has thick ground cover but few trees. Most trees in this area are located in rows ("Abrigos") that separate pastures. Despite a lack of dense forests, we recommend siting the array in this area because of other notable strengths. The relatively flat terrain will permit the deployment of all array elements and noise filters of any dimension at the same elevation. This site has the clearest views to the horizon of any site on Sao Miguel. There is very little cultural activity in this area. This site is ~ 10 km from the nominal station coordinates. The site at the nominal station coordinates was not selected due to local hydrothermal activity, strong winds and cultural activity.

We recommend an array with an aperture of 2 km. Wind speeds and infrasonic noise levels are often high in the Azores. As a result, we further recommend an augmented array of 8 elements with five of the elements to be deployed in a 300 m aperture area at the center of the large-scale array. We recommend that four of the central elements be equipped with 20 m noise filters.
We recommend that one of the inner sites is also equipped with a 70 m filter. We recommend all outer elements be equipped with 70 m filters. We recommend that the central recording facility is located at the top of a small hill, Pico do Gato, near the center of the array.

There is very little publicly owned land in the Azores. The land at 7 of the 8 sites we have selected, and at the location of the central recording facility, is privately held. To reduce the costs of establishing and operating an array in this region, and to minimize the impact that the array would have on local islanders,

we recommend locating the sensors at points where the tree rows intersect. Although this area would accommodate space filters of any dimension, we further recommend space filters that are embedded within the rows of trees. If necessary, full scale (18 to 70 m diameter) space filters can be deployed at all sites we have chosen.

During the winter months, the effectiveness of any infrasound monitoring station in the Azores will be strongly dependent on time. During our survey, rapid noise level swings of 40 to 50 dB at 0.1 Hz were not uncommon.

1.1 INTRODUCTION.

A network of 60 infrasound stations (Figure 1-1) is being established as part of the International Monitoring System (IMS) to monitor compliance to the Comprehensive Nuclear-Test Ban Treaty (CTBT).

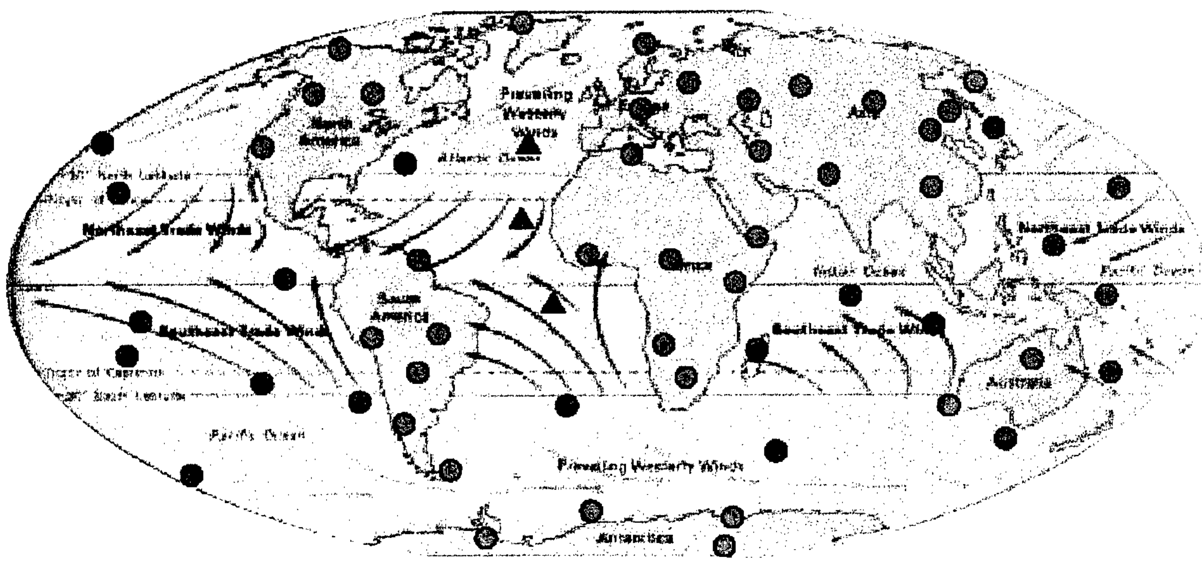


Figure 1-1. Planned global IMS infrasound network. The 3 triangles in the Atlantic from north to south are the Azores, Cape Verde and Ascension with the background display of oceanic winds adapted from the World Book Encyclopedia.

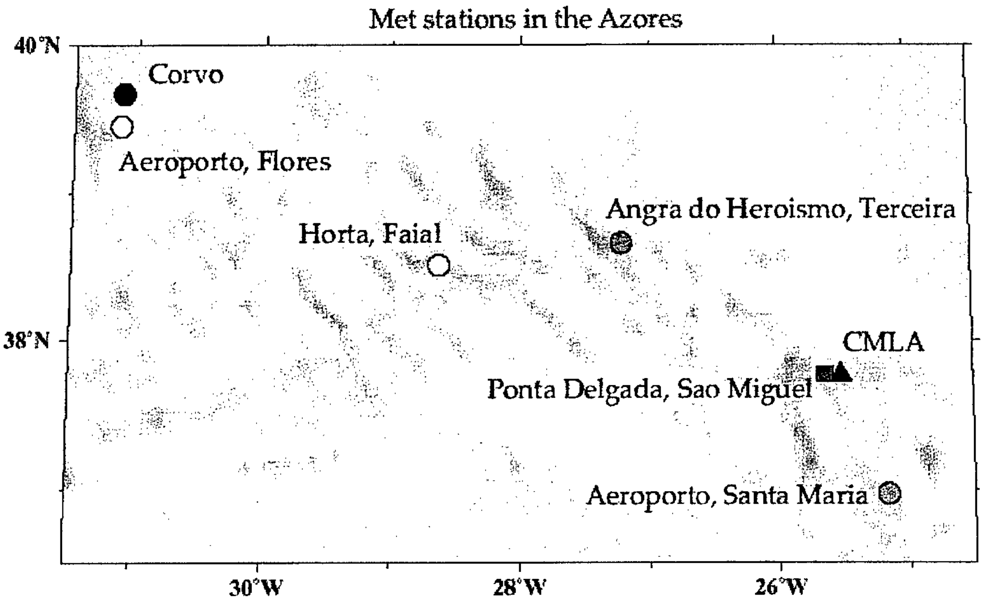


Figure 1-2. The Azores archipelago with long term meteorological stations indicated by colored circles. Locations of GSN station CMLA and the archipelago are the main island, Sao Miguel and above the mid-Atlantic ridge respectively.

The network includes 23 oceanic island stations: one of these (IS42) is to be in the Azores, Portugal. This report summarizes the survey that was conducted by researchers at the University of California, San Diego in November and December of 1998 to find a good location for the IS42 array. The survey was conducted in accordance with guidelines described in the Provisional Technical Secretariat (PTS) site survey document CTBT/PCIV/WGB/1, Appendix VI.

1.2 ORGANIZATION OF THE REPORT.

This section reviews all elements of the Azores site survey including the preliminary site selection, the survey, data analysis, final conclusions and recommendations.

1.3 GENERAL DESCRIPTION OF THE SURVEY AREA.

The Azores archipelago includes 9 islands (Figure 1-2). The islands are located in the mid-Atlantic roughly 1300 km from Portugal at a latitude of 38° N. The main island in the archipelago is Sao Miguel (Figure 1-3). This island spans approximately 70 x 10 km and has a population of 125,000. Topography on Sao Miguel is dominated by three active stratovolcanoes, each of which has erupted at least once in the last 700 years (Panduronga Dessai, personal communication). The highest point on the island is Pico de Vara at 1103 m. Eroded and vegetated mounds of soft welded tuffs or pumice dominate much of the fine-scale topography of the island. There are naturally occurring fumaroles in the east-central part of the island. The central, youngest, part of the island has no significant topography but is subject to relatively strong winds due to funneling around significant topography on both sides. All the islands in the Azores were once densely forested however the islands have been occupied since the 15th century and most of the trees have been cleared for agricultural or urban use. Most flat lying areas have been converted into a patchwork of pastures separated by stone walls or tree rows known in Portuguese as "Abrigos". Some dense forests exist in the more rugged areas.

Sao Miguel, Azores

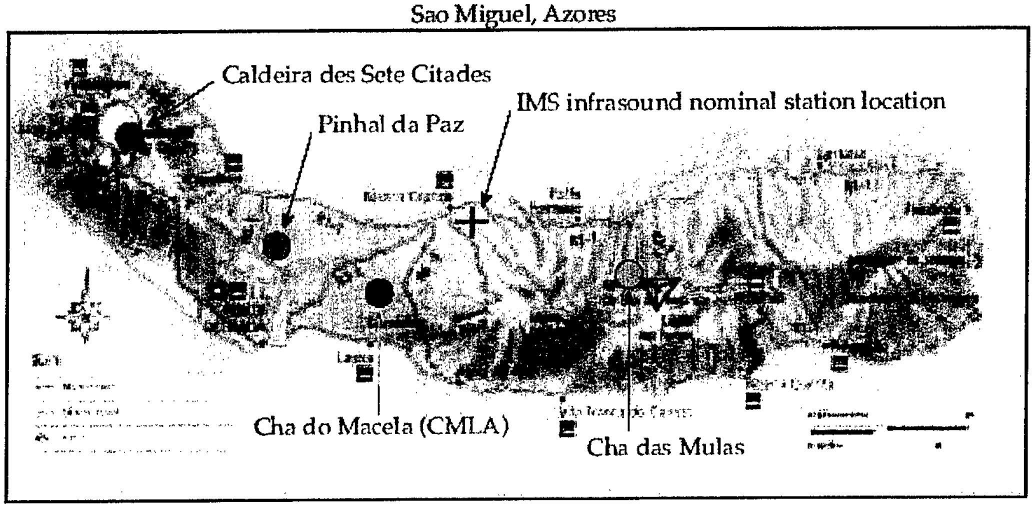


Figure 1-3. Sao Miguel, Azores and the 4 survey locations with the western site located in a calderra, the two central sites in dense forests, Cha das Mulas on a plateau, which has a rich low-level ground cover, and the recommended configuration indicated by the red triangle.

1.4 METEOROLOGICAL CONDITIONS.

Meteorological data have been collected by Instituto Nacional de Meteorologia e Geofisica in the Azores for over 3 decades at the sites indicated in Figure 1-2. These data indicate that winds on the main island, Sao Miguel, are relatively weak (Figure 1-4). The Azores lie in the prevailing westerlies, and winds are strongly influenced by local pressure cells. In the summer a high pressure cell normally lies over the northern islands (Pedro Mata, meteorologist at Portugal's Instituto de Meteorologia). Clockwise air circulation brings winds to Sao Miguel from the northeast. For the rest of the year western winds dominate. The faintness of the winds at the station in Ponta Delgada on Sao Miguel is at least in part due to shielding this large island provides from these winds. The winds are weakest during the summer. Our survey occurred in November and December of 1998, a time of relatively strong winds.

1.5 SITE SELECTION.

The meteorological data, together with land ownership ground cover, topography and infrastructure maps, guided us in our selection of survey sites. We located all survey sites on the main island, Sao Miguel for the following reasons.

- Meteorological data indicate that winds are relatively weak on this island.
- The island is the site of the nominal station location (Figure 1-3).
- The Global Seismographic Network (GSN) station CMLA is located on the island.
- Sao Miguel is the largest island in the Azores.
- The airport at the main city, Ponta Delgada, has regular jet service from Lisbon and Boston.

Wind speed in the Azores

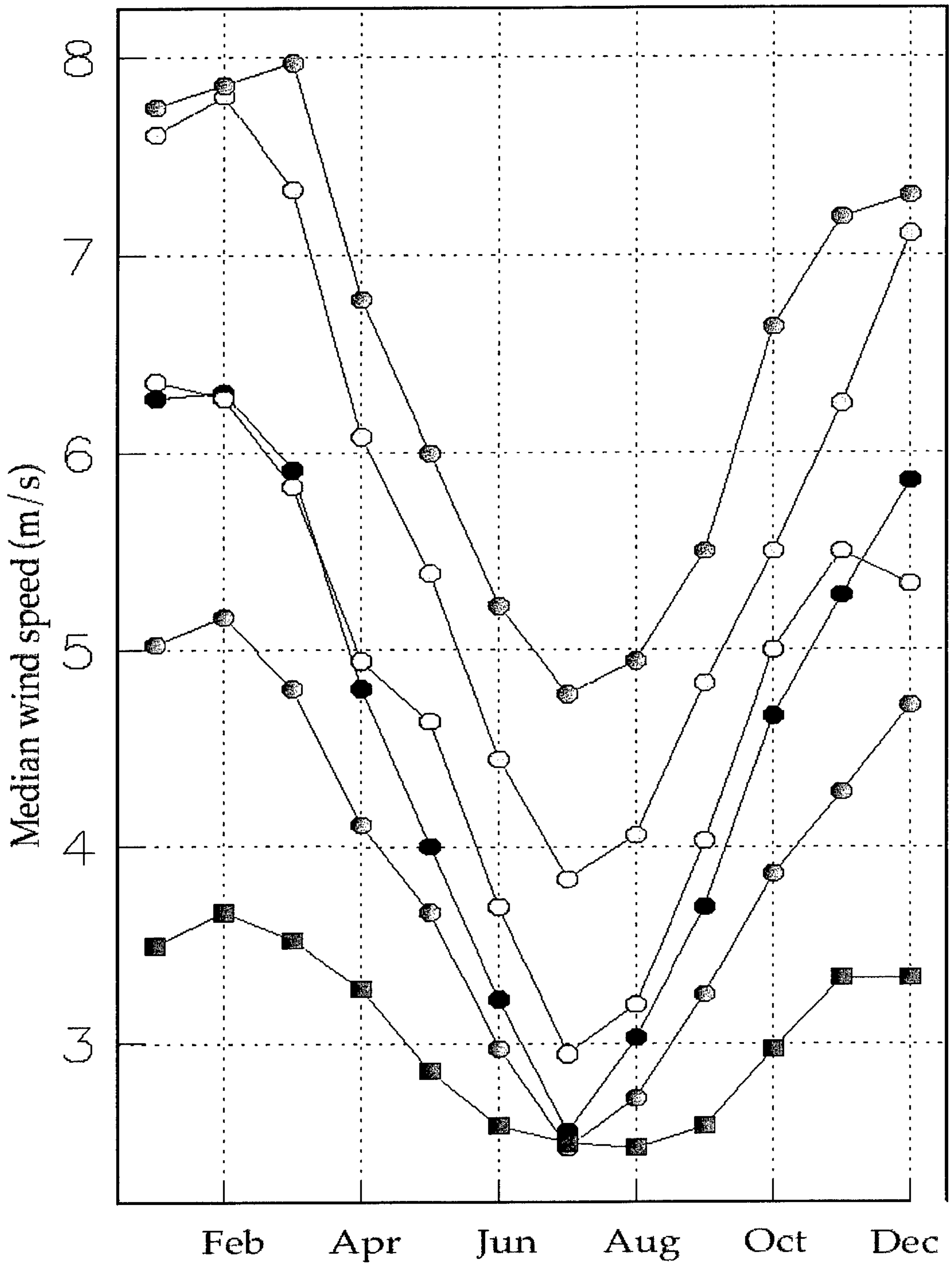


Figure 1-4. Meteorological data collected in the Azores at the sites indicated in Figure 2 with each set of points color coded to match [data collected 1951 - 1980 and published in "OClima de Portugal", Instituto Nacional de Meteorologia e Geofisica, ISSN 0870-4767, 1991].

• Expert technical support is located at SIVISA (Sistema de Vigilancia Sismologica dos Acores) in Ponta Delgada.

After a careful review of the entire island during a site visit in April, 1998, four survey points were selected. The four survey points were selected to sample diverse means of reducing wind noise. These locations in order from west to east are listed below. The nominal location was not surveyed as this area is densely populated (Figure 1-3), is the site of considerable hydrothermal activity and is subject to strong winds from the north. One important drawback of Sao Miguel, and all other islands in the Azores with the exception of Flores, is a lack of publicly held land. All four survey sites that we review below are located on, or near, some government land. However none of these parcels are large enough to accommodate all elements in an infrasound array. Flores was not chosen for the survey as it is small and remote, however 80% of the land on that island is owned by the Azores government.

1.5.1 Caldeira das Sete Cidades.

A large, 5 km diameter, calderra is located at the west end of the island (Figure 1-3). The most recent eruption occurred there in 1287 AD (Booth et al., 1978). The small population within the calderra is concentrated in Sete Cidades. The calderra was chosen as a survey point as it is large enough to accommodate an infrasound array. The walls of the calderra are up to 275 m high. With the survey we intended to quantify the noise reduction, if any, that results from shielding provided by the walls.

1.5.2 Pinhal da Paz.

This location is in a dense forest of a variety of deciduous and non-deciduous trees. It is located near the long axis of the island north of Ponta Delgada (Figure 1-3). The most common tree is the Criptomeria Japonica pine (otherwise known as a Japanese Cedar). These trees reach a height of 20 to 25 m. The park is owned by the government and covers 43 hectares. A similar area to the west, which is held by the military, covers 49 hectares. The Portuguese expect power and telephone service into the Pinhal da Paz park within 2 years. It would be difficult to deploy large (70 metre aperture) noise filters in this forest due to a shortage of large, flat, spaces.

1.5.3 Cha do Macela.

Cha do Macela is located in a thick Criptomeria forest in rolling topography (Figure 1-3) to the east of the central, low, part of the island. This site is co-located with the GSN station CMLA and lies closest to the nominal infrasound station location.

1.5.4 Cha das Mulas.

The fourth site, Cha das Mulas, was situated on a broad plateau near the east end of the island (Figure 1-3). The plateau is ~550 m above sea level and has large pastures separated by rows of Criptomeria trees. An area of rolling hills, roughly 580 m above SL. Without considering the infrasonic data, this appears to be the best site on the island. There are some large clusters of trees. The area is in the center of island between significant topography at the east end and to the west in the center of the island and thus we might expect some shielding from the NE and W winds. There are no significant hills in the area and thus site lines to the horizon are very good. There is almost no cultural activity except for infrequent traffic on secondary roads.

1.6 SURVEY EQUIPMENT.

1.6.1 Micro-barometer.

For our survey we used the MB2000 aneroid microbarometer fabricated by the French Dèpartement Analyse et Surveillance de l'Environnement (DASE). These sensors provide a filtered signal between 0.01 and 27 Hz (cut back to 9 Hz by an anti-aliasing filter) with an adjustable sensitivity. We deployed the low sensitivity (20 mV/Pa) version. The electronic noise of the sensor is 2 mPa rms, between 0.02 and 4 Hz, which is well below natural background noise (DASE technical manual, 1998). At each site the microbarometer was placed in an insulating case at ground level.

1.6.2 Meteorological sensors.

At each of the four sites we used a Handar 425A ultrasonic wind velocity sensor, which has a sensitivity of .005 mV/m/s and 11.5 mV/°. This sensor has no moving parts as it uses an array of 3 ultrasonic transducers. Travel time of ultrasonic pulses from one transducer to another is measured and is used to estimate wind velocity. This sensor was located on a mast 2m above the ground. We used Handar 435C relative humidity/air temperature sensors, which have sensitivities of .01V/°C and .01V/1% humidity. The temperature and humidity sensors were located beneath the wind sensor at an elevation of 1 m. These sensors were equipped with a solar radiation shield.

1.6.3 Space filters.

For the surveys we deployed identical filters at all sites. Each sensor was equipped with a simple, 4 arm, 30 m aperture cross composed of microporous hose. At each site, porosity extended from the wall of the insulating case to a sealed cap at the outer end of the hose.

1.6.4 Data acquisition systems.

The infrasound and meteorological signals were digitized at 20 and 1 sps respectively using a 24 bit Reftek 72A-08 data acquisition system. At each site data were recorded locally on a Reftek 72A-05 2 GB disk. Each system was run on solar power with 2 deep cycle 12V batteries serving as a backup in case of severe cloud cover.

1.6.5 Microbarometer calibration.

The Atlantic site survey was preceded by calibration tests in the field at the Pinon Flat Observatory (PFO) in southern California, and in the laboratory at IGPP in La Jolla, California. The tests were conducted to ensure all field systems were robust and yielded equal digitized signals for equal input.

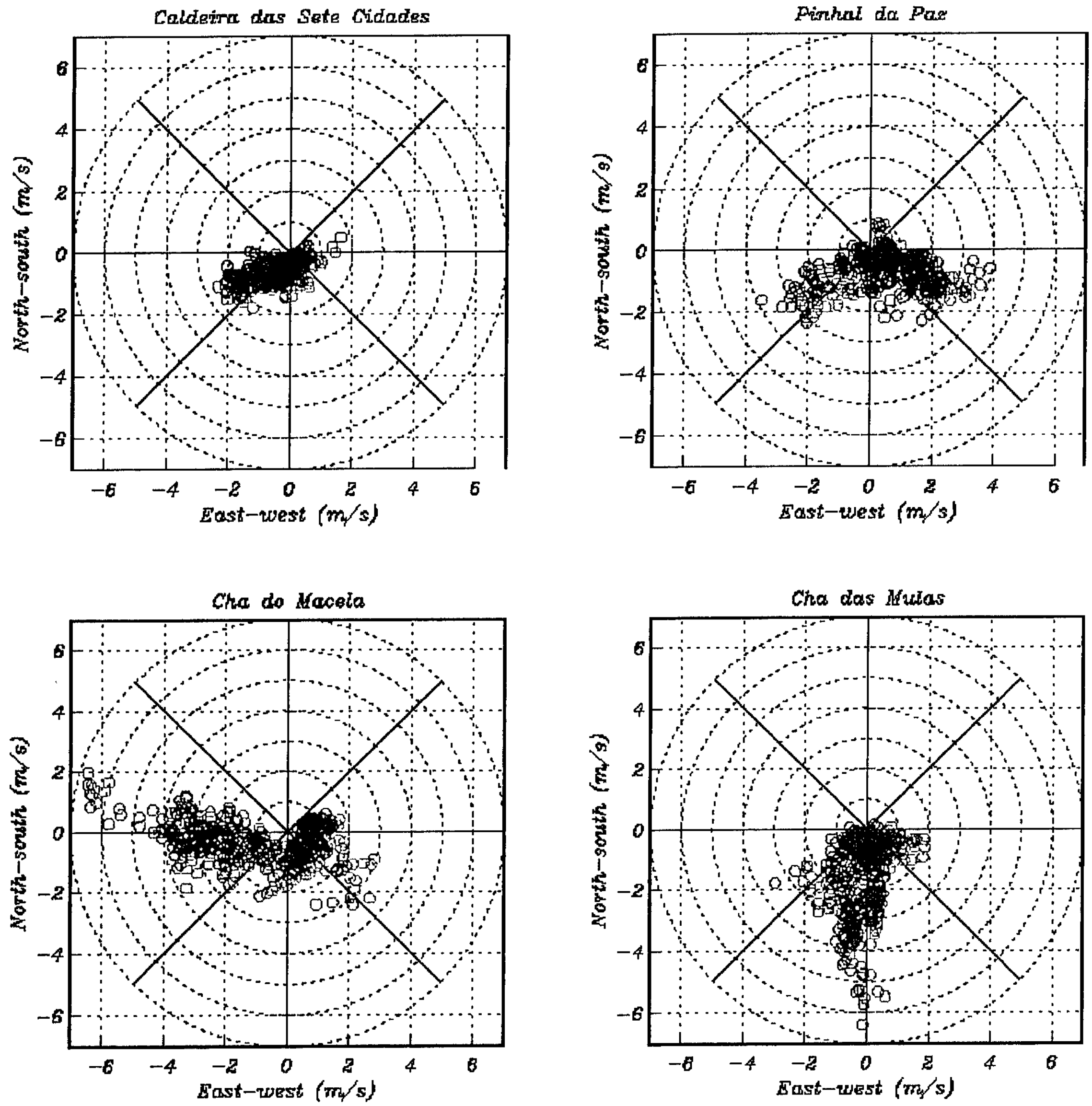


Figure 1-5. Wind velocity at the four sites [At the time of the survey the wind usually comes from the south however the wind is clearly different at all four sites].

1.7 EXPERIMENTAL RESULTS.

The 4 survey points on Sao Miguel, Azores were occupied for a 19 day period in November and December of 1998.

1.7.1 Meteorological conditions during the survey.

In Figure 1-5 we display wind velocity at the four sites during the survey. These displays are based on 454 estimates of wind speed taken at each site. Each estimate is based on the average wind velocity in a 15 minute period at the beginning of each hour of the experiment. During the survey, the dominant wind direction at the four sites was from the south (Figure 1-5). Winds are weakest in the calderra.

At that location, the average instantaneous wind speed during our survey was 0.87 m/s. The winds were strongest in the forest at Cha da Macela (1.87 m/s on average).

1.7.2 Power spectral analysis method.

All field data were downloaded from the Reftek disks and placed in CSS3.0 format databases. To examine the spectral content of the filtered data we used Welch's method (Welch, 1967) which yields a single power spectral estimate from an average of several taken at regular intervals in the time range of interest. The spectral estimates we have used in this study were derived from an average of 4 estimates, each taken from consecutive 204.8 s intervals.

1.7.3 Noise levels at the survey sites.

Fifteen minutes of pressure and meteorological data from the Azores experiment are shown in Figure 1-6. The unfiltered pressure time-series from the station at Cha das Mulas exhibits 30 second period fluctuations superimposed on substantially longer period energy. The shorter period variations dominate the filtered record (second panel). In this time period, minor wind velocity fluctuations are constant. The temperature and humidity vary relatively slowly. The detailed structure of the filtered pressure record results from the superposed contributions of myriad atmospheric phenomena. Our study is concerned primarily with the dependence of the noise on frequency and the exact location of the sensor and thus we will focus on the spectral properties of the noise.

The Welch power spectral density taken from the filtered record (Figure 1-7) shows a decay in power levels from the peak at 30 s to the corner of the anti-aliasing filter at 9 Hz. A weak microbarom peak is centered at 0.2 Hz.

From the full 3 weeks of recording at all 4 sites we calculated power spectral denstiy at 454 time intervals.

Each interval began at the turning of the hour and lasted for 15 minutes (such as the interval displayed in Figure 1-6). Tenth, 50th and 90 percentile noise levels at all frequencies from 0.005 Hz to 10.0 Hz are shown in Figure 1-7. At times of relatively low noise the microbarom peak is obvious at all sites. This figure shows that the interval displayed in Figure 1-6 was a time of relative quiescence. From this figure it is evident that the longer periods depend more strongly on time. For example, the spread between the 10th and 90th percentiles is 50 dB at 0.1 Hz and just 20 dB at 1.0 Hz.

The same spectral character is seen at all four sites (Figure 1-8). Median noise levels between 0.03 and 0.1 Hz are 5 to 10 dB lower in the calderra and in the forest at Pinhal da Paz than on the plateau at Cha das Mulas and at Cha do Macela. At other frequencies the noise levels are comparable. The noise spikes at 3.5 and 7.0 Hz at Pinhal da Paz are likely due to infrequent industrial activity. That survey point is near several quarries. The spikes are extremely band limited and are likely due to large equipment used to process the mined rock. A comparison of noise levels in the Azores with levels recorded at 4 other IMS infrasound sites are shown in Figure 1-9. Infrasound noise levels in the Azores are relatively high.

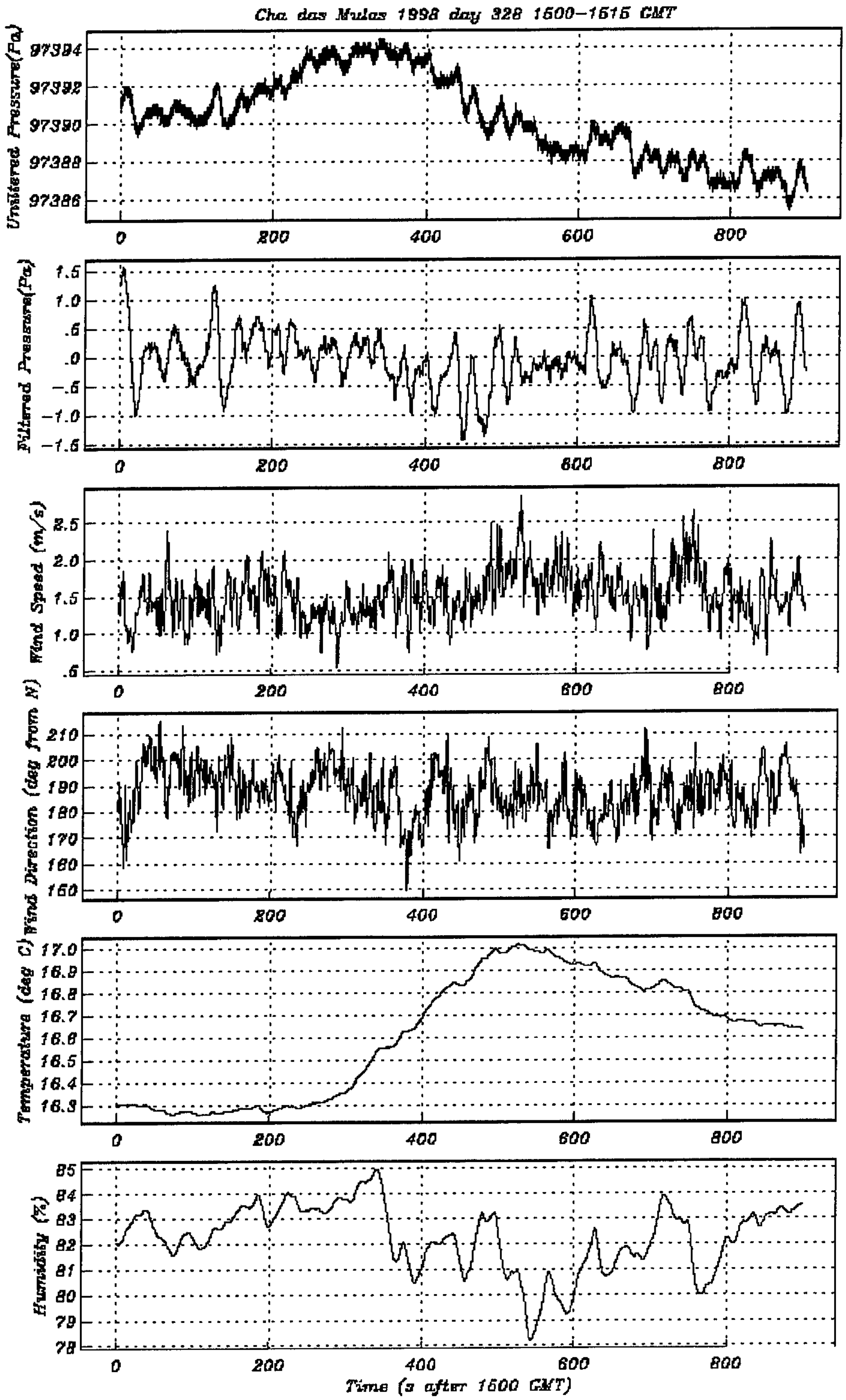


Figure 1-6. Atmospheric pressure and meteorological data from 15 minute intervals starting 15:00 GMT at Cha das Mulas with raw and filtered pressure data shown in upper two panels and Wind speed, direction, temperature and humidity shown below.

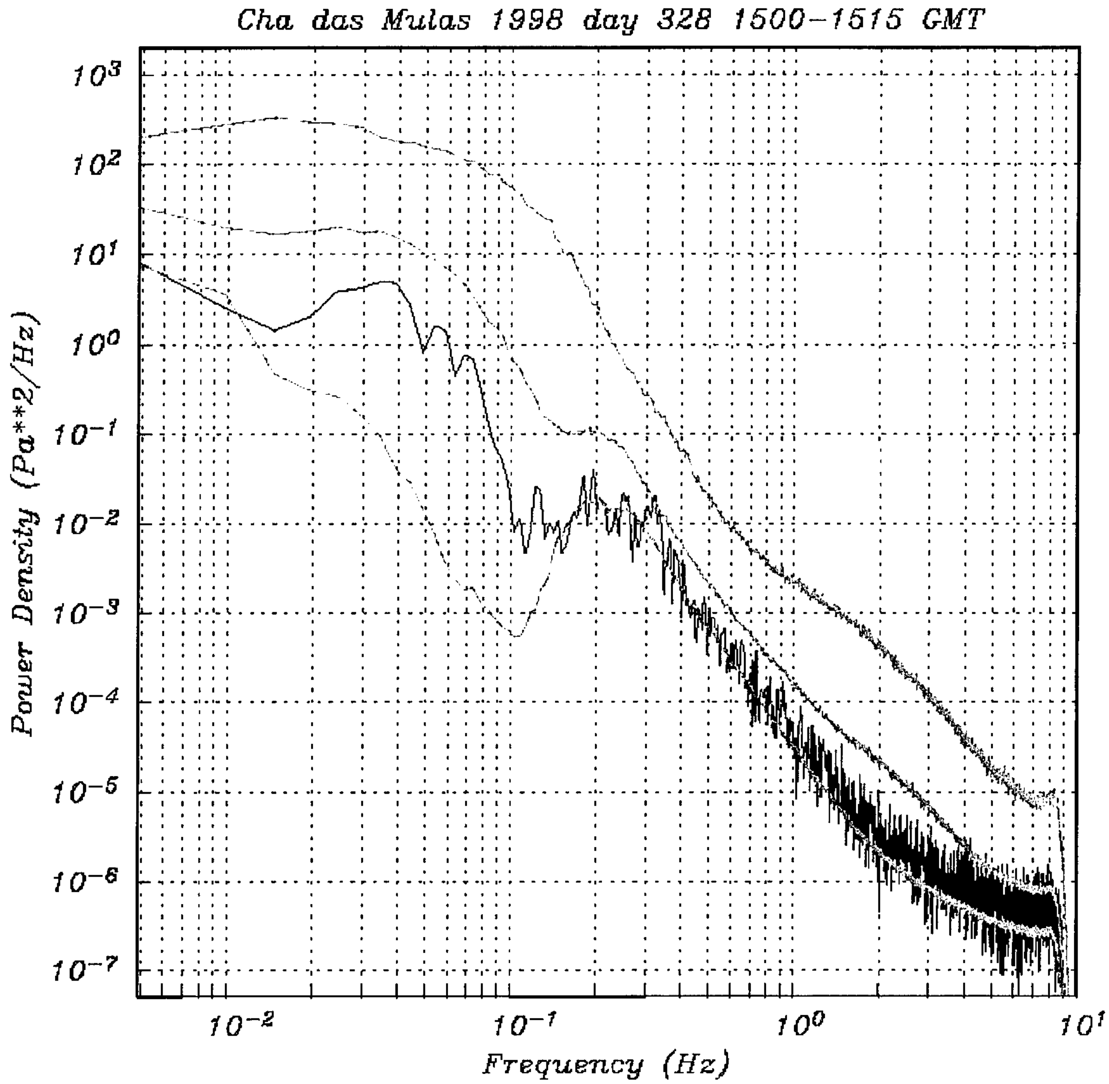


Figure 1-7. Noise power density at Cha das Mulas with a single power density estimate, taken from the filtered pressure data displayed in Figure 1-6, shown in black and the colored curves representing the 10th, 50th and 90th percentile noise levels from the entire experiment. [These curves are based on 454 noise level estimates taken at 1 hour intervals with each estimate taken from 15 minutes of data].

As expected, the noise power in the band between .005 Hz and 10 Hz is highly dependent on wind speed. In Figure 1-10 we display the power spectral density at several frequencies between .02 and 5 Hz as a function of wind speed. The wind speeds depend strongly on the site. In the calderra the winds at an elevation of 2 m reach ~ 2.5 m/s. The winds are strongest in the forest at Cha da Macela where they reach 6.8 m/s. The winds are slightly weaker on the plateau at Cha das Mulas (max. 6.4 m/s) and are somewhat weaker in the forest at Pinhal da Paz where they reach a maximum of 3.9 m/s. Winds in the calderra are sharply reduced by the walls of the calderra which are 200 to 300 m above the central floor. The forest at Cha da Macela is thick however this location is adjacent to the topographically low, central, part of the islands where winds appear to be relatively strong. Figure 1-10 shows that the infrasonic

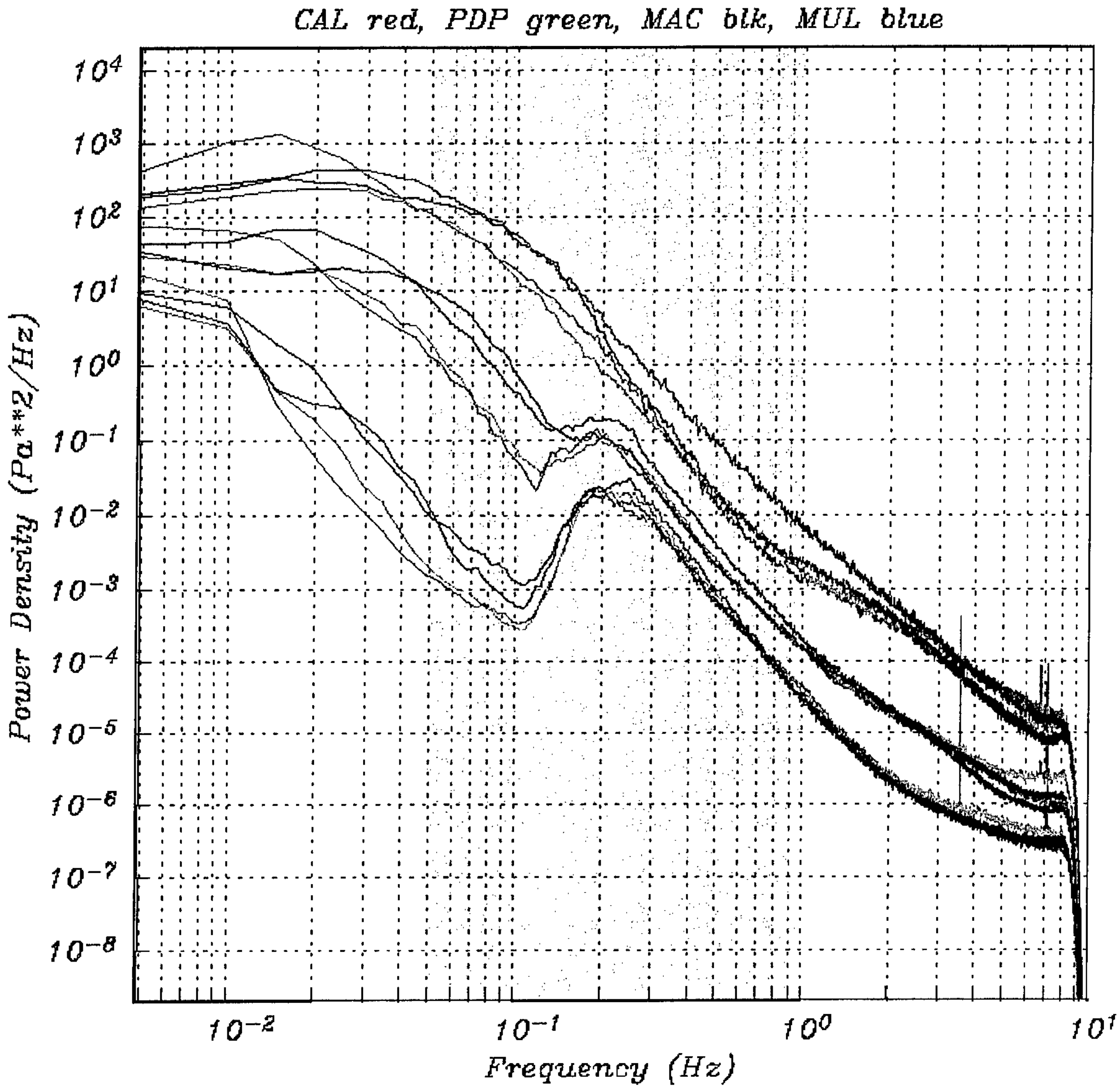


Figure 1-8. Tenth, 50th and 90th percentile noise curves at the four sites surveyed in the Azores [Between 0.02 and 0.2 Hz, noise at Cha das Mulas and Cha do Macela is 5 to 10 dB higher than in the calderra and in the forest at Pinhal da Paz, while at higher frequencies, median noise levels are comparable at all sites, though most signals of interest to the monitoring community lie in the shaded band].

noise at all frequencies between .02 and 5 Hz depends strongly on wind speed, however, the dependence is complicated by the highly variable wind azimuth. In the Azores, mobile pressure cells have a dominant influence on local wind and thus the wind direction is highly variable. This variability is strongly dependent on receiver location. As a result, at each site there is a time variant interaction of wind flow and local topographic features and thus the complex scaling of wind power with wind speed (Figure 1-10). The winds are weakest in the calderra however at this location the noise power at long periods increases most rapidly with wind speed. The noise power increases relatively slowly at Cha das Mulas. This is perhaps because of the remoteness of this site from any rugged topography.

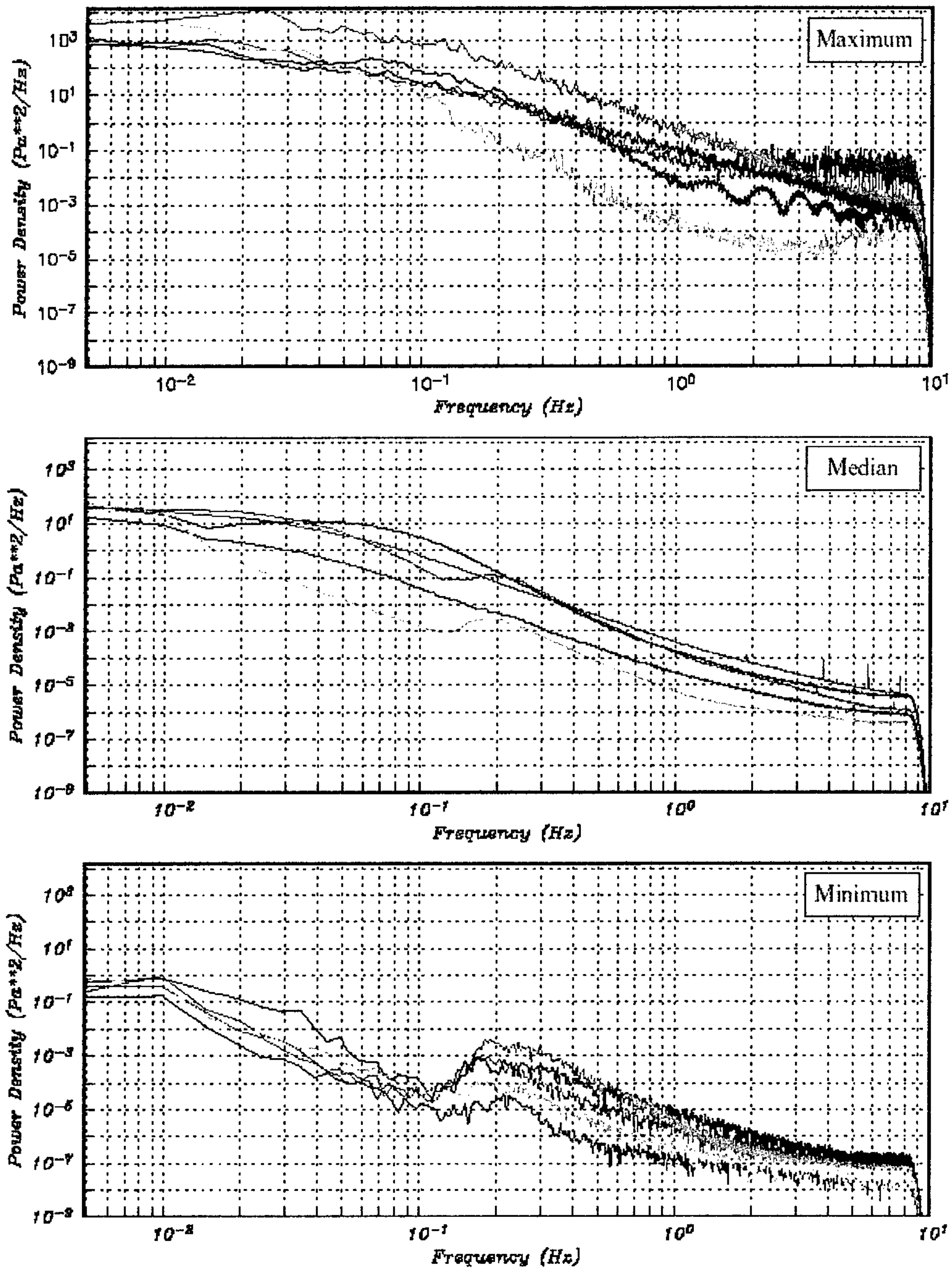


Figure 1-9. Maximum, Median and Minimum noise levels at 5 IMS infrasound locations with the Azores represented by the green curves and in order, Ascension island, Cape Verde, Pinon Flat, California and Newport, Washington represented by the red, blue, black and orange curves.

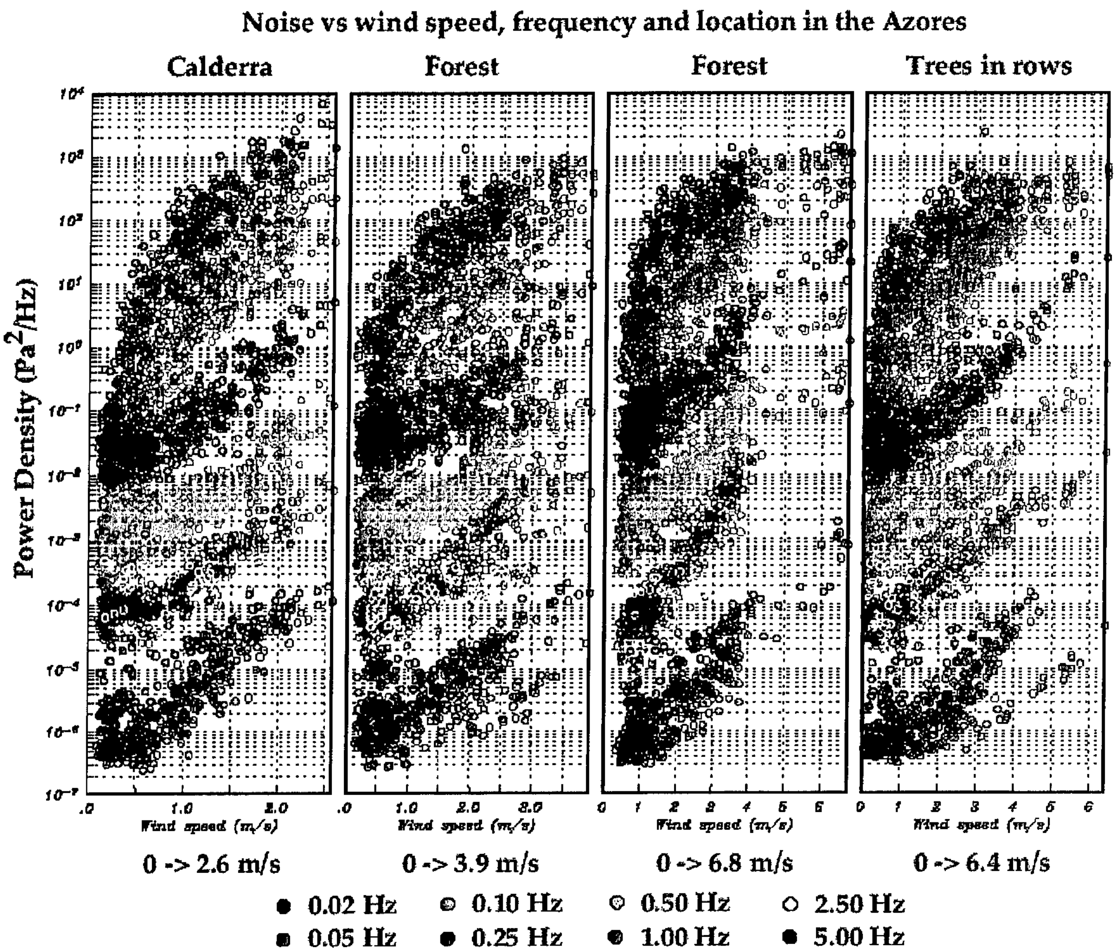


Figure 1-10. Dependence of infrasonic noise on wind speed and frequency at the four sites in the Azores, with, from top to bottom in each panel, noise power at 0.02 Hz (black); 0.05 Hz (red); 0.1 Hz (green); 0.25 Hz (dark blue); 0.5 Hz (light blue); 1.0 Hz (pink); 2.5 Hz (yellow); and 5.0 Hz (black).

1.7.4 Temporal Variations in Noise Levels.

Extreme changes in wind speed and noise levels are common in the Azores in the winter. The experiment in Nov. and Dec. occurred at a time of advancing inclement weather. Toward the end of the experiment wind speed at Cha das Mulas could increase from 1 to 6 m/s in a few hours. Commensurate noise power increases of 40 to 50 dB at 0.1 Hz occurred (Figure 1-11). In Figure 1-12 we show a sonogram of power density at frequencies below 5 Hz. The microbarom is seen for a brief period near the middle of the interval considered in this figure. Noise levels vary much more strongly with time than location. Periodically, any infrasound station on Sao Miguel will be "deafened" by wind noise. At times of high wind, the microbarom noise is obscured. Rapid changes in wind speed and noise levels, and thus in the effectiveness of any infrasonic station to sense signals from distant events, are not uncommon - at least in the winter in the Azores.

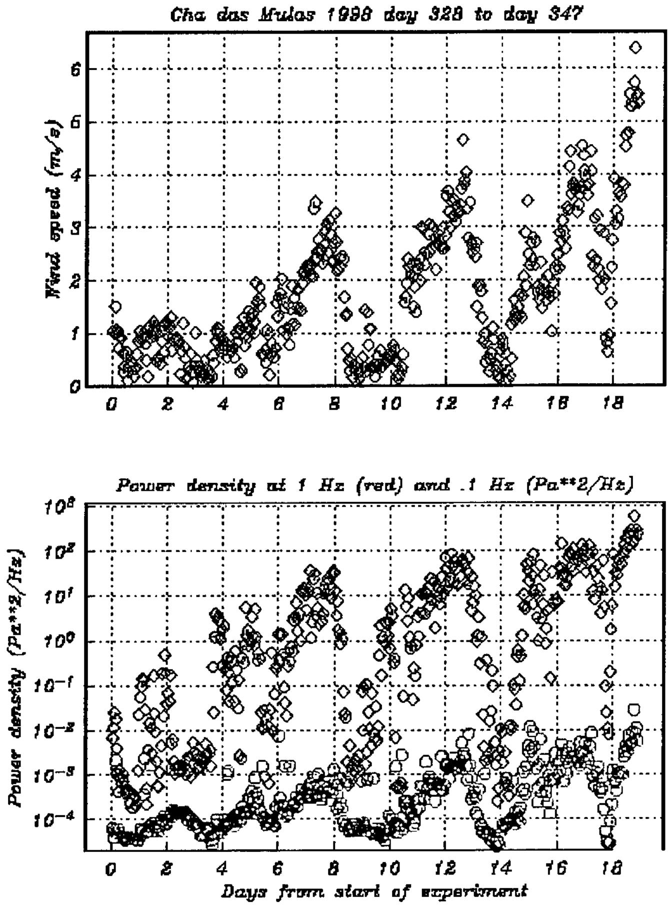


Figure. 1-11. Noise power and wind speed as a function of time at a station in the Azores with wind noise at 0.1 Hz (upper sequence of points in the lower panel) and at 1.0 Hz tracking closely the wind speed.

1.7.5 Observed Infrasonic Signals.

An example of infrasonic signals is given in Figure 1-13. This filtered pressure record was taken from day 333 starting at 12:00 GMT at the station in the forest at Pinhal da Paz. We deployed a single sensor at this site and thus have no location for these events however this site is located near several quarries.

1.8 CONCLUSIONS AND RECOMMENDATIONS.

The principal conclusions of this report are the location and the configuration of the infrasound array we are recommending for the Azores. These points are discussed in Sections 1.8.1, 1.8.3 and 1.8.4. We discuss the validity of our survey results in Section 1.8.2. In Sections 1.8.5 through 1.8.12 we discuss the expected performance of this array and the logistics of establishing and maintaining the infrasound array.

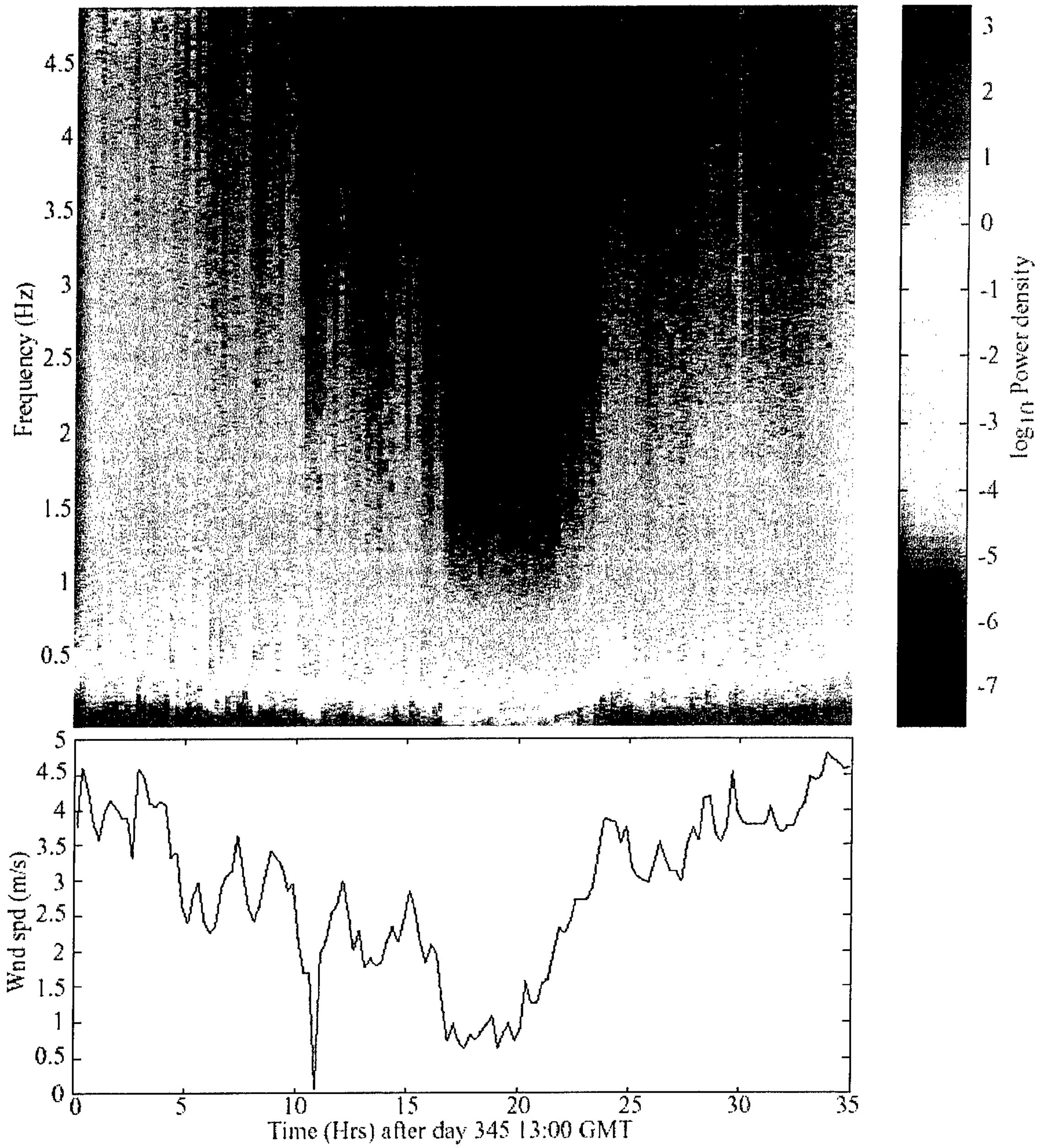


Figure 1-12. A sonogram of the log (base 10) of the power density of infrasonic noise between 0 and 5 Hz during a storm near the end of our survey showing the micorbarom at the middle of this time interval when the wind speed was at a minimum.

1.8.1 Determination of the most suitable site.

The primary objective of this field program is to identify the location in the Azores that is most suitable for a permanent IMS infrasound array. The paramount factor is infrasonic noise however our selection has been guided by practical considerations. A site that offers low infrasonic noise but gives few options for siting a permanent array might not be optimal. The ideal site is large enough to allow any array

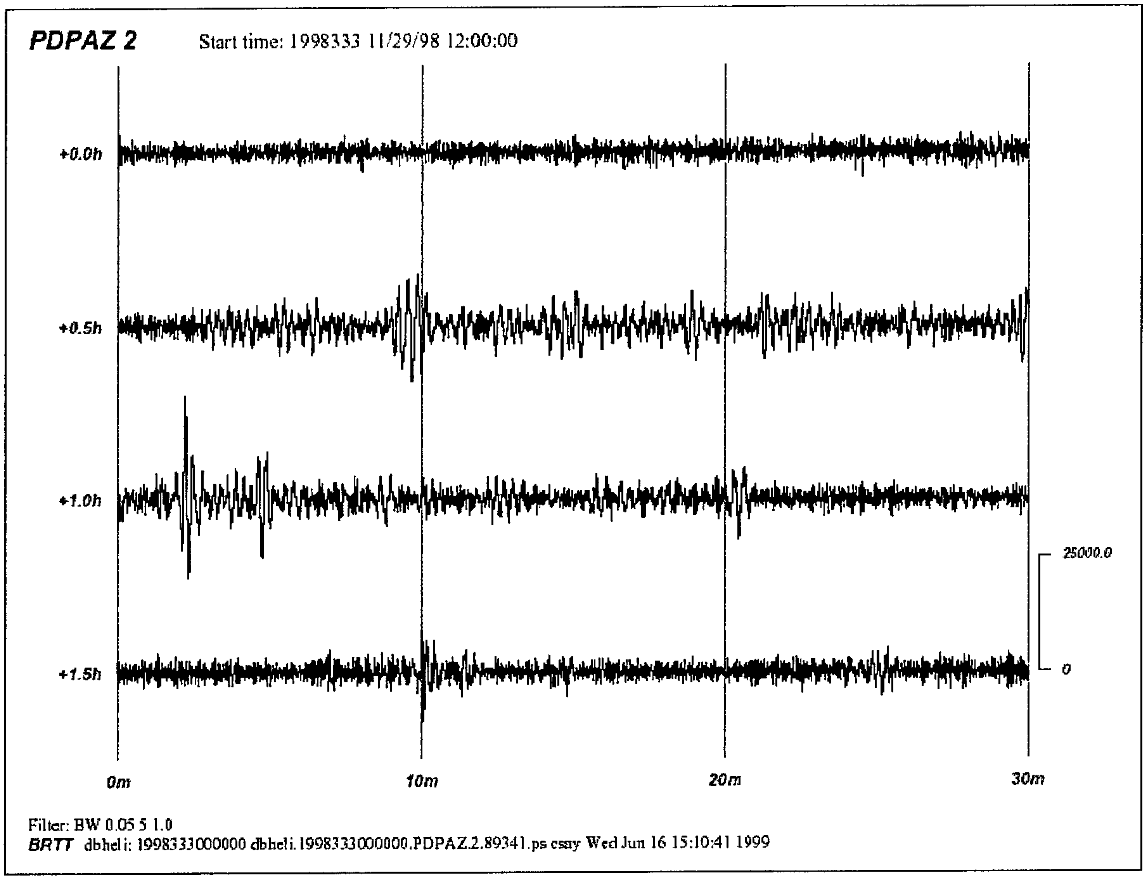


Figure 1-13. Some infrasonic signals recorded at Pinhal da Paz, each trace spaning 30 minutes with the data having been bandpassed between 0.05 and 1.0 Hz and the vertical scale (in counts) indicated at the lower right.

configuration from 1 to 3 km aperture to be considered. On Sao Miguel, the only site that could accommodate *any* IMS array design is Cha das Mulas. From every perspective other than the most important one, noise, the plateau is clearly the best site and it will serve as the standard against which we judge all other sites in the Azores. In addition to plenty of space to deploy array elements at the same elevation, there are unobstructed views to the horizon from most points. There is little cultural activity and the site is relatively far from the ocean. Most of the plateau is covered by grass. Long hedges or rows of Criptomeria trees interrupt wind flow.

We now assess noise levels at the sites shielded from the wind by dense forests and topography relative to the noise levels on the plateau. We also assess the utility of these areas for accommodating an infrasound array.

1.8.1.1 A comparison of two sites in dense forests with Cha das Mulas. In the Azores, the dependence of infrasonic noise on wind speed is not straightforward but is complicated by the azimuthal variations of the wind. As we show in Figure 1-10, there is considerable scatter of noise levels about a general trend to increased power at higher wind speeds. In the thickest forest at Pinhal da Paz (where

the tallest Criptomeria trees reach a height of ~ 25 m), the winds at an elevation of 2 m are weaker than those observed on the plateau at Cha das Mulas. At Pinhal da Paz, the maximum wind speed was 3.9 m/s and at Cha das Mulas the maximum wind speed was 6.4 m/s. The average instantaneous wind speed at Pinhal da Paz during our survey was 1.32 m/s and was 1.71 m/s at Cha das Mulas. Despite the reduction in wind speeds, it is apparent that the infrasonic noise levels at frequencies below 0.1 Hz are not sharply reduced. Figure 1-10 indicates that at Pinhal da Paz, noise levels between 0.05 and ~0.1 Hz are reduced by 5 to 10 dB relative to those observed on the plateau at Cha das Mulas.

The Pinhal da Paz site has several drawbacks that we believe are more significant than the observed gains in noise levels. The forested park at Pinhal da Paz consists of rolling hills in an area of ~ 43 Hectares. The topography, and the limited extent of the park, severely limit array design. There are very few points in the park at which small space filters could be deployed at a constant elevation. If this area were selected for the permanent deployment it might be necessary to use wind screens. The Pinhal da Paz area is a recreational park situated 10 km north of Ponta Delgada. There is considerable cultural activity in this area, and as a result, security is a greater concern than it is on the plateau at Cha das Mulas. There are several centers of industrial activity that have led to elevated high frequency noise levels at Pinhal da Paz. For these reasons, the Pinhal da Paz forested site is not preferred over the plateau at Cha das Mulas.

The second forested site, Cha da Macela, is subject to high winds directed through the central, low, part of the island (Figure 1-3). Although median noise levels are comparable to those at Cha das Mulas, 90th percentile noise levels are high. Despite the proximity to the Global Seismographic Network station CMLA and the nominal infrasound coordinate (Figure 1-3) this site is also not preferred.

1.8.1.2 A comparison of a site shielded by topography with Cha das Mulas. Wind flow that is laminar prior to passage over a two-dimensional ridge becomes turbulent on the lee side (Kaimal and Finnigan, 1994). The turbulence results when the wind flow, which is compressed and accelerated at the ridge crest, decompresses on the lee side. A separation bubble forms at the location where some air flows in the opposite direction, back to the ridge, and is followed by a turbulent wake. The site in the calderra was chosen for our survey to determine if this turbulence would contribute significant noise at long periods or if, overall, the walls of the calderra would deflect the wind away from the site and reduce noise levels.

As shown in Figure 1-5, wind speeds in the calderra are relatively low. The average instantaneous wind speed in the calderra during our experiment was 0.87 m/s while the wind on the plateau averaged 1.71 m/s. Figure 1-10 indicates that noise levels are clearly elevated at .02 Hz and suggests the presence of unusually energetic large-scale turbulence in this area. Figure 1-8 displays essentially the same result as it indicates that this noise enhancement at ~ 0.02 Hz is most pronounced on the 50th and 90th percentiles - i.e,. when noise and wind speeds are elevated. It is difficult to make definitive conclusions about noise levels at higher frequencies because of the scatter in the noise estimates. However it is apparent that although the calderra is effectively reducing wind speeds, noise levels between 0.05 Hz and ~ 0.2 Hz are reduced by < 5 dB when wind speeds are high. Noise levels in the calderra above 0.04 Hz are comparable to those at Pinhal da Paz (Figure 1-8). When the wind is near-average, the calderra noise levels between 0.05 and ~ 0.15 Hz are comparable to those in the forest at Pinhal da Paz and 5 to 10 dB lower than on the plateau at Cha das Mulas (Figure 1-8).

Most signals of interest lie between 0.05 and 1.0 Hz (Christie, 1999) and so this discrepancy could be important. Because of short duration of the survey (~ 3 weeks) it is not clear if this noise spread is significant and indicates relative noise levels throughout the year. The calderra is large enough to accommodate an IMS infrasound array and could be an excellent site however it offers few options for array configurations. Two large lakes and a village lie within the calderra. Just one array configuration is possible - 4 elements in an isosceles triangle 2 1/2 km tall and 1 1/2 km at the base. As shown in Figures 1-8 and 1-10, noise levels at long periods are elevated - probably due to wind flow across the rim of the calderra. For these reasons, and because of the potential for signal blockage at most azimuths due to the walls of the calderra, this location is not preferred over Cha das Mulas.

1.8.1.3 The most suitable site. Our survey indicates that the best site in the Azores is at Cha das Mulas. This broad plateau is large enough to accommodate any array configuration. Our brief survey indicates that this area is subject to substantial noise level swings (Figure 1-11) however comparable noise swings occurred at all sites on Sao Miguel (and presumably at all other islands in the Azores). Any infrasound monitoring station located in the Azores will offer a highly variable performance - particularly during the winter when storms are not uncommon. As shown in Figure 1-4, our survey was conducted at a time of relatively strong winds. Although we have observed significant winds, we expect better performance at most other times of the year.

1.8.2 Validity of Survey Results.

Because of limited resources and manpower, this infrasound site survey lasted just 3 weeks. This gives just a glimpse of the full range of meteorological conditions that will occur in a typical year. Is it fair to assume that the brief period sampled is representative of the entire year and the survey will allow us to recommend the best site or is a 2 to 3 week survey too brief to be useful? For a brief survey to be ineffective, climactic conditions at the time of the survey would have to be out of the ordinary and tilt the balance of infrasonic noise so that the relative noise levels at the sites are not representative of the yearly average. Intuitively, this seems rather unlikely and easy to check. The chief source of infrasonic noise is turbulence due to wind flow over topography. If wind direction changes in such a way that the wind-topography interaction at the time of the survey is unusual and, as a result, little turbulence is generated at certain sites, or excessive turbulence is generated at others, the brief survey taken at that time would be misleading. It should be possible to rule out this scenario by comparing wind velocity measurements made during the survey with those from long-term meteorological observations. A significant discrepancy in wind speed or direction recorded in an area with rugged topography would be cause for concern. The winds observed during the Azores survey appear to be consistent with long term observations. Both surveys occurred at times of elevated winds, but these winds were as expected from historical data. There is no reason to believe that these winter surveys are misleading. We believe that a survey conducted at any time of the year would lead us to the same conclusion.

1.8.3 Proposed Permanent Array Configuration.

As discussed by the PTS site survey document CTBT/PCIV/WGB/1, Appendix VI, the surveys are to consider infrasound arrays with apertures between 1 and 3 km. Large arrays permit more accurate estimates of the back azimuth of infrasound sources but require highly coherent signals. Smaller arrays have poorer resolution, however are preferred at locations where signal coherence is poor. At sites

where noise, most notably the microbarom, is highly coherent, larger offsets between array elements might be required. The survey we conducted in the Azores did not produce data collected by closely spaced sensors. As a result, we have no concrete evidence regarding signal and noise coherence at this location. Due to the strength of the microbarom in the Azores, and the presence of high noise due to winds the array, we recommend an array with an aperture of ~ 2 km. Although the standard IMS array is to include just 4 sensors, infrasonic noise levels in the Azores are high and we believe adequate array performance will require an augmented array of 8 elements. The preferred array is depicted in Figures 1-14 and 1-15 with topography and infrastructure. This array includes 5 elements in a central area ~ 300 m across. In Figures 1-16 through 1-19, we show photos of the central area and of the outlying sites in the proposed array with detailed drawings of the proposed filters, local vegetation (hedges) and infrastructure.

GPS coordinates of the array sites and the central processing facility (CPF) are as follows. Sites 1 through 4 are in the inner, high-frequency optimized, array. Sites 5,6 and 7 are in the outer, long-period, array. We propose both short-period and long-period elements at Site 1.

Table 1-1. Recommended coordinates for elements in Azores infrasound array.

	Latitude (°N)	Longitude (°W)	Elevation (m)
Site 1.	37° 46.99′	25° 22.26′	552
Site 2.	37° 47.00′	25° 22.44′	555
Site 3.	37° 46.36′	25° 22.46′	560
Site 4.	37° 46.84′	25° 22.26′	558
Site 5.	37° 47.29′	25° 22.32′	553
Site 6.	37° 46.14′	25° 22.32′	567
Site 7.	37° 47.18′	25° 21.62′	522
CPF	37° 46.89′	25° 22.61′	585
VSAT	37° 46.88′	25° 22.61′	608

All of these sites, except for the southern site in the outer array, are located on private land. The local government owns the land at the southern site. The government agency that owns a small parcel of land on which the southern site lies is the Servico de Desenvolvimento Agrario de Sao Miguel. This agency is part of the Agriculture Department of the Regional Government of the Azores.

Signal blockage in this area is not an issue. Likewise, turbulence from air flow off nearby topography should not be a serious consideration. With the exception of some horizon blockage caused by small nearby hills, all topography lies below 10° above the horizontal. At most sites, the horizon lies less than 3° above the horizontal at virtually all azimuths.

1.8.4 Array response.

The impulse response of this array configuration is shown in Figure 1-20. All values are normalized to 1 at the peak of the mainlobe. The impulse response has been calculated at wavenumbers between +/- 1.5 cycles/km. These wavenumber limits include acoustic energy at wavenumbers down to that of a 0.5 Hz

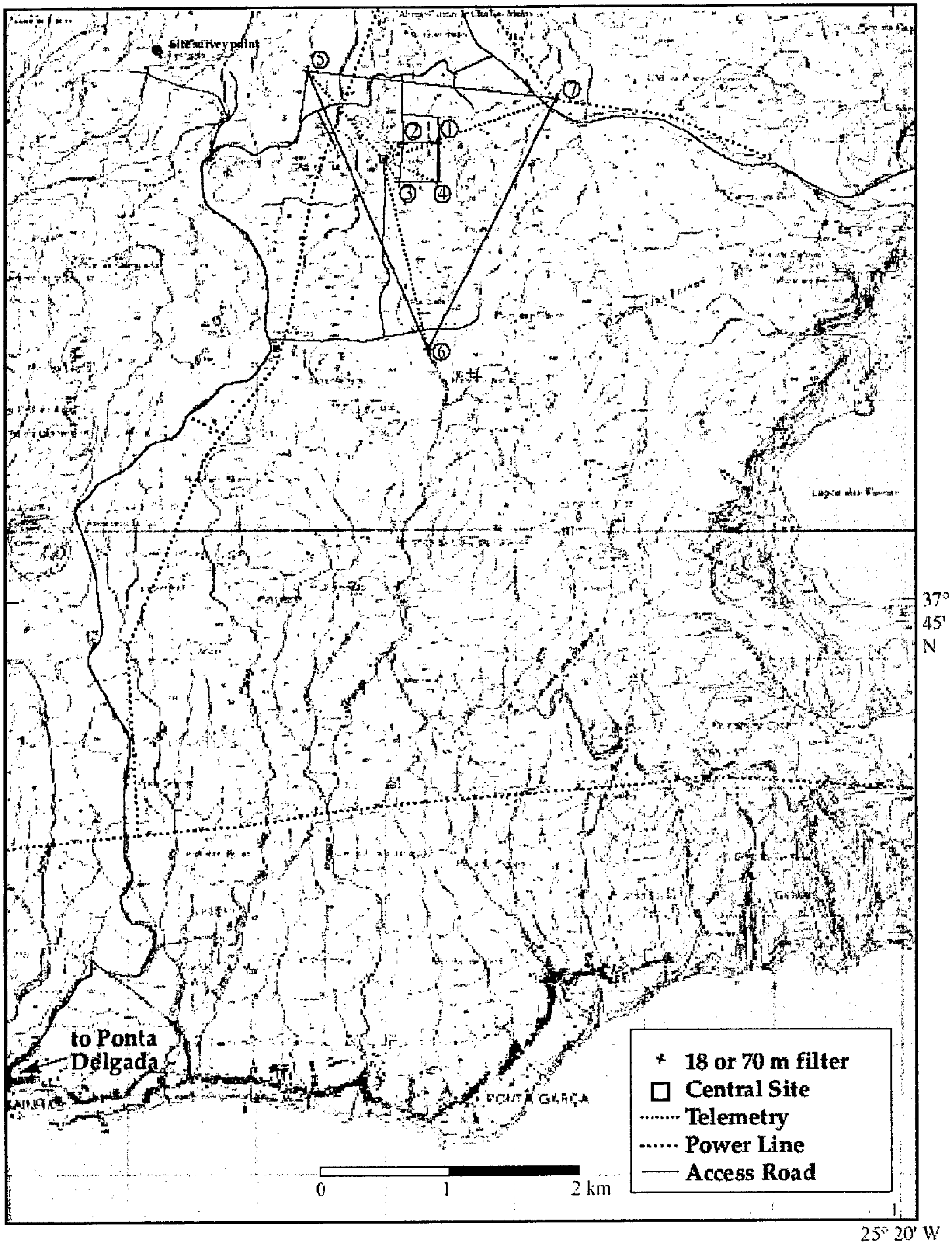


Figure 1-14. Tentative array locations at Cha das Mulas with sites 1 through 4 in the central area, sites 5, 6 and 7 are in the outer array and access roads, power lines, telemetry links, array elements and the central recording site highlighted.

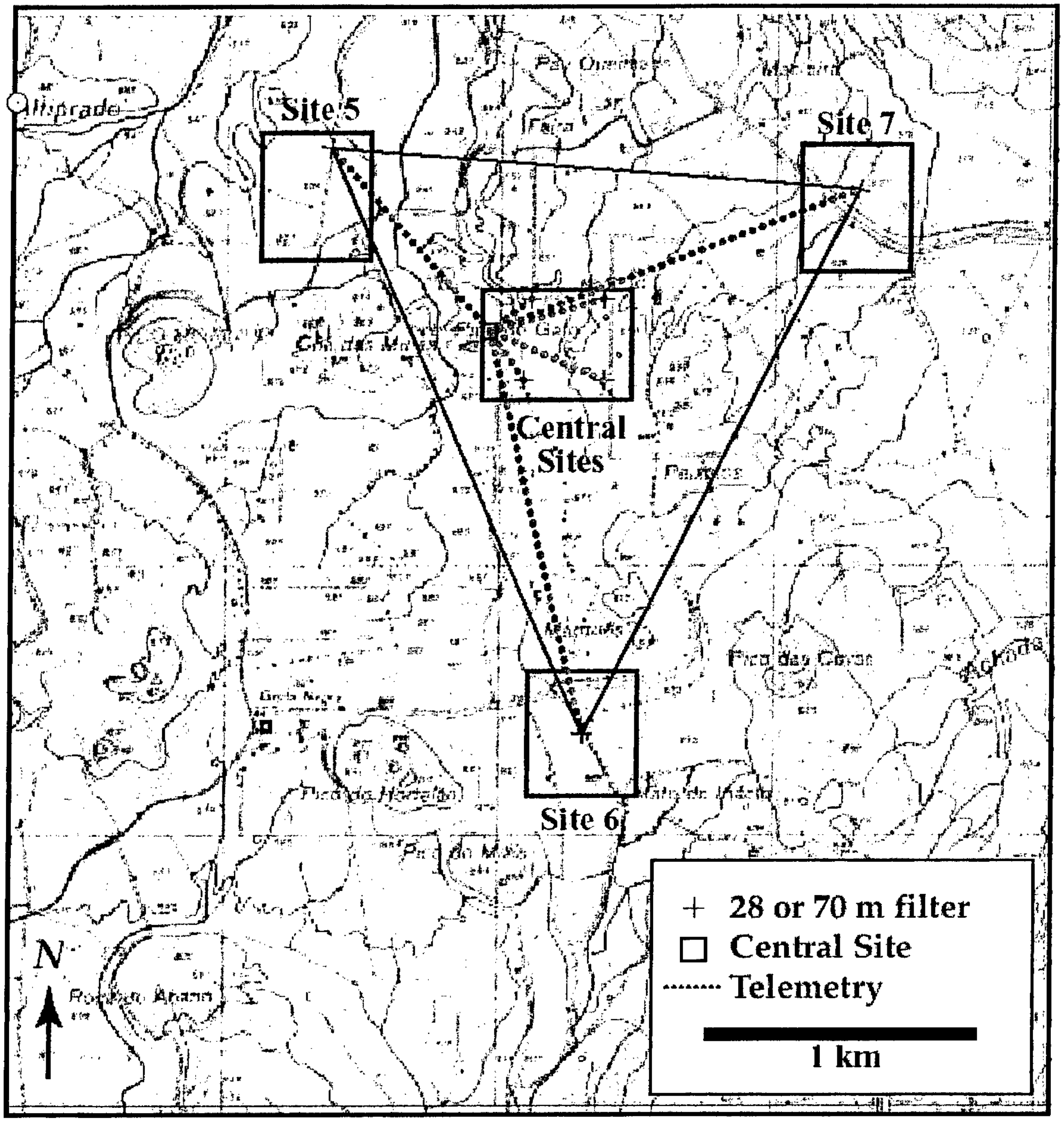


Figure 1-15. Closeup view of proposed array with the Cha das Mulas survey site represented by the yellow symbol to the west of the proposed array and detailed drawings of the central siteand sites 5, 6 and 7 in the next 4 figures.

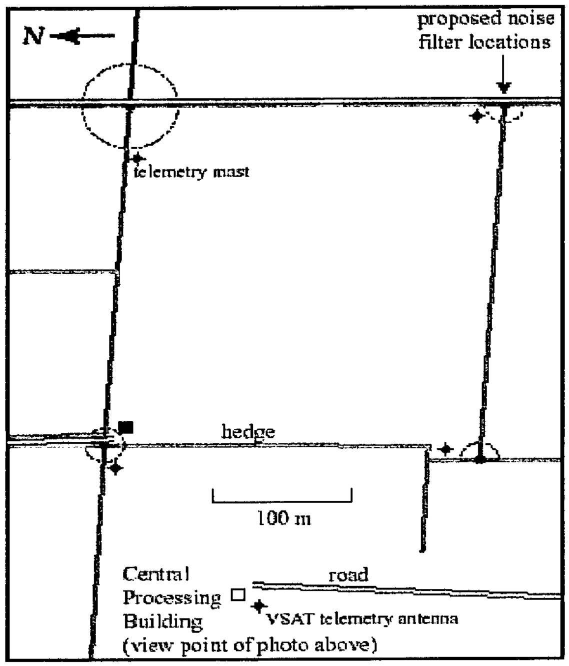
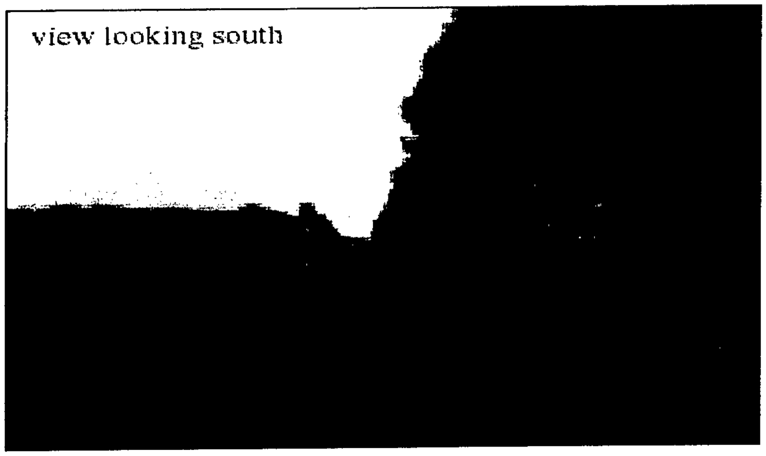


Figure 1-16.The photos were taken from the summit of Pico do Gato with Pandu Dessai in the foreground. Panorama of central part of the Cha das Mulas array is shown at top and the Drawing of proposed filters and infrastructure is below, with the white arraws indicating the hedge corners that we are recommending be used for stations in the infrasound array.

horizontally propagating wave. The impulse response has several sidelobes at wavenumbers between 0.75 and 1.0 cycles/km. The sidelobes peak at ~60% the amplitude of the mainlobe. The dominance of the mainlobe in this array response calculation is largely due to the addition of extra elements near the center of the array.

1.8.5 Wind-noise reducing space filters.

In this area, as at all other points on Sao Miguel, land ownership will likely be a significant issue. With the exception of one site, all sites in the array displayed in Figures 1-14 and 1-15 are on privately owned land. The southern site is on a small government owned parcel. For this reason, and because there a tendency in the Azores to make maximum use of all land, it is beyond doubt that space filters that average noise over large areas would be costly to establish and to maintain and would be relatively inconvenient for the local population.



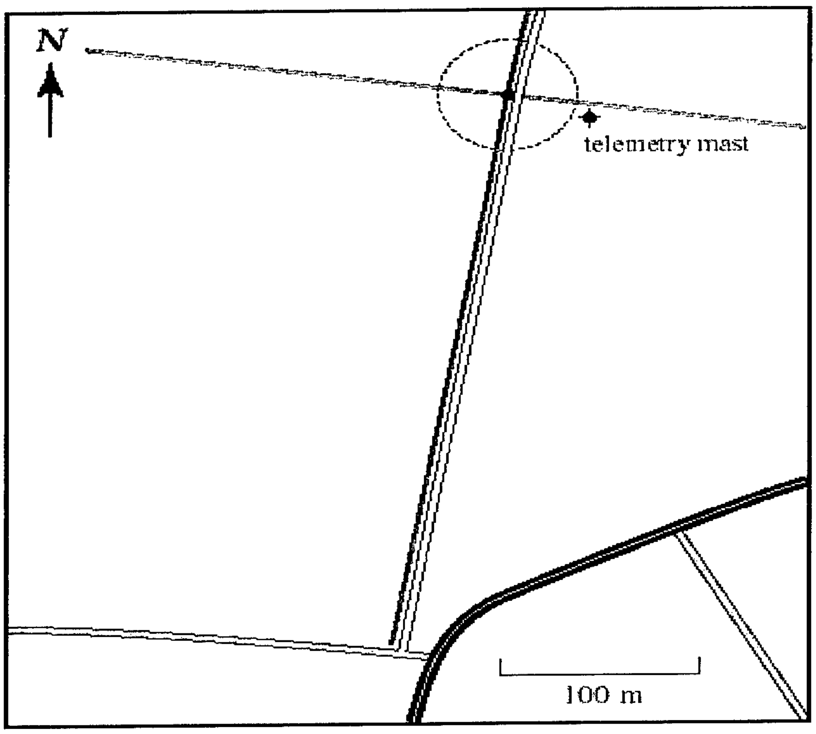


Figure 1-17. Photo at site 5 (the northwest site) is shown at top with drawing of the proposed filter, hedges (or tree rows) and roads shown at the bottom.

Most land at Cha das Mulas has been cleared of trees and converted into pastures. As shown in Figures 1-16 through 1-19, the pastures are separated by rows of trees (known as "Abrigos"). We have concluded that the best overall space filter design in this area is one in which noise reducing space filters are embedded within the tree rows. We recommend that the sensors be located at points at which the tree rows intersect (as illustrated in Figures 1-16 through 1-19). In consultation with Doug Christie, we believe equipping the outer stations with 70 m aperture noise filters should enhance the effectiveness of the outer array for detecting long period (20 s to 1 Hz) signals. We recommend that the stations in the

view looking south

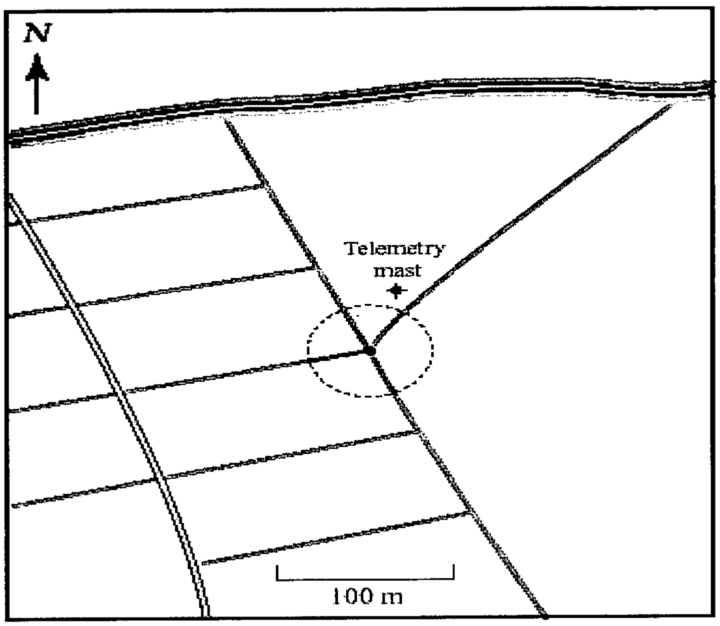


Figure 1-18. Photo at site 6 (the southern site) is shown at top with drawing of the proposed filter, hedges (or tree rows) and roads shown at the bottom.

inner 300 m aperture mini-array be equipped with 20 m aperture space filters to improve detection of high-frequency (1 to 4 Hz) signals with one site (Site 1) also equipped with a 70 m filter.
We recognize that an arrangement of 4 linear space filters is unlikely to provide the sensitivity and the omni-directionality made possible by the "multi-port" design preferred by the PTS. UCSD is about to begin a research program funded by the U.S. Defense Threat Reduction Agency (DTRA) into what linear configurations are best and to quantify the difference between linear designs and the multi-port design.

1.8.6 Utility of an infrasound site at this location.

There are numerous requirements for a good infrasound station (Christie, 1998). The exceptional island might meet all of them. Noise is the most important consideration. There are a plethora of noise sources - only a subset are of interest to us. Wind noise is the paramount concern. As we have seen, wind in the

view looking south

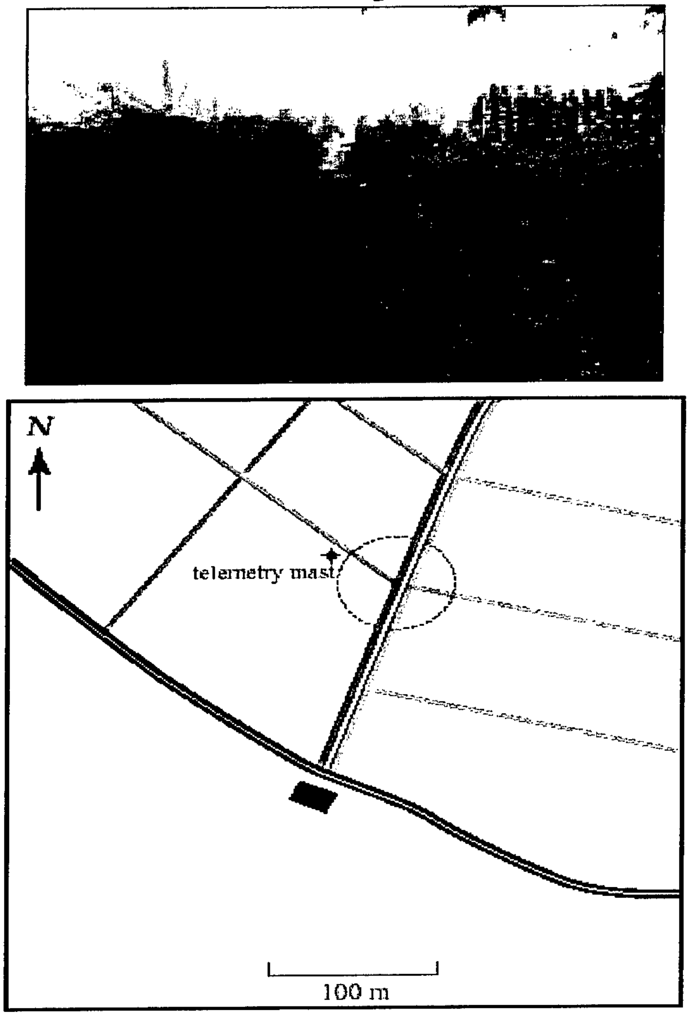


Figure 1-19. Photo at Site 7 (the northeastern site) is shown at top with drawing of the proposed filter, hedges (or tree rows) and roads shown at the bottom.

Azores in the early winter at least is capricious. This is not a trait of just oceanic sites but it is reasonable to expect such conditions to be more common on islands. Changes in wind speed of 5 to 6 m/s in a few hours appear to be common in the early winter in the Azores. No infrasound station deployed in the Azores will deliver invariant performance through the year. At times of high wind, such a station will be rendered ineffective for sensing all but the most energetic signals.

1.8.7 Central recording facility and VSAT antenna.

We recommend that the central recording facility be located on Pico do Gato. The summit of this hill is ~ 40 m above the surrounding areas. There is a line-of-site between the summit of Pico do Gato and each of the array elements. The hill is located near the center of the proposed array (Figure 1-15). A

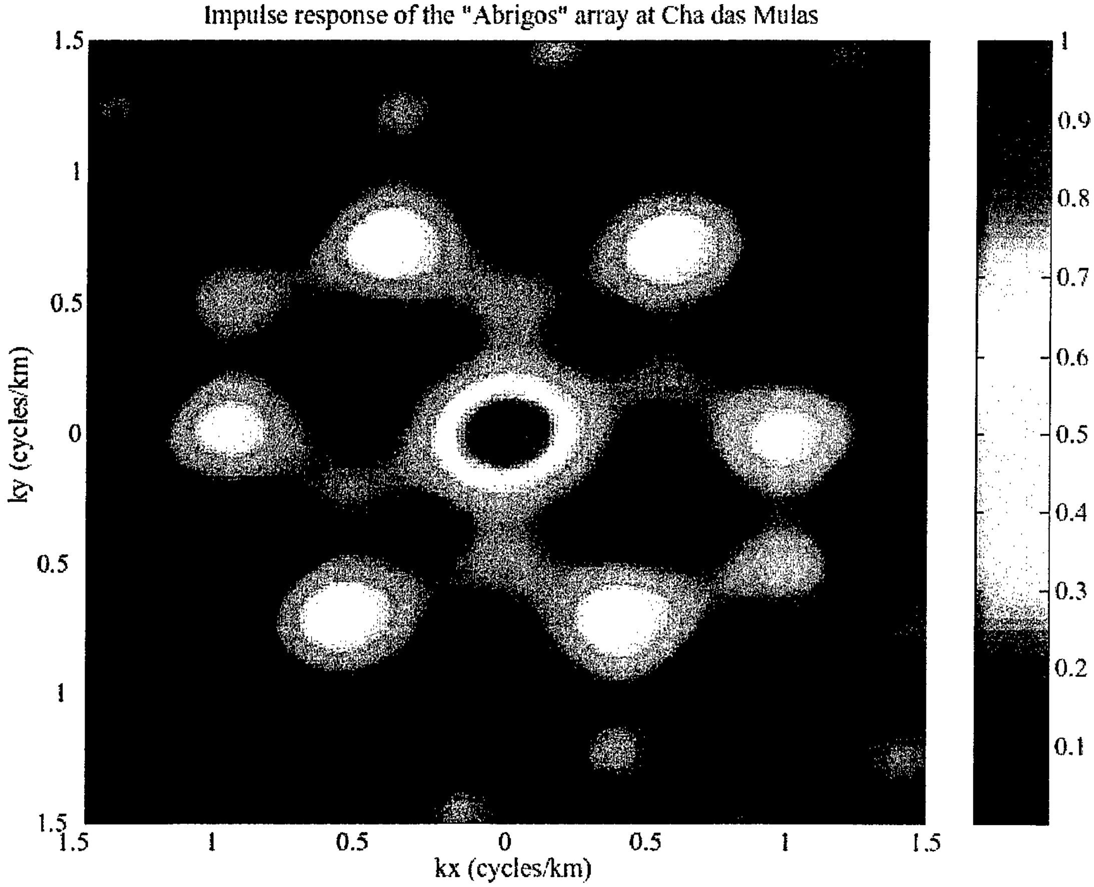


Figure 1-20. Impulse response of the "Abrigos" array at Cha das Mulas which includes elements located at the intersection of hedge rows with the outer array being triangular, and the inner array square.

road to the top of this peak exists however it would have to be upgraded. There is no building on this hill. A small building would have to be built at this location to house the equipment.

The VSAT telemetry antenna would be located on Pico do Gato. This site has unobstructed views to the horizon at all azimuths.

1.8.8 Communications.

The authority that controls the frequencies for communications in the Azores is Instituto de Communicacoes de Portugal. A license is required for transmissions at frequencies between 900 MHz and 2.2 GHz. The license requires an annual fee. Transmission of data by spread spectrum radios in the range of 2.4 GHz and 2.4835 GHz is free, as long as the transmitter power doesn't exceed 10 dBW (1 Watt) of Effective Isotropic Radiated Power (EIRP). We recommend 2.4 GHz spread spectrum transmissionbetween the array elements and the central recording facility on Pico do Gato. Our preference is wireless Local Area Network (LAN) radios produced by Freewave Technologies, Inc (http:// info@freewave.com). These radios are relatively inexpensive and come with an Ethernet interface. The

power levels required for transmission between array elements and the central processing facility is below 1 Watt of EIRP. Additional information on these radios is available via the internet from moreinfo@freewave.com.

The Pico do Gato hill has been cleared of trees. As a result, the radio telemetry will not require a substantial mast. We recommend a 3 m mast at this location. All sites, except Site 6, have a clear view to Pico do Gato. Site 6 is south of an east-west tree row in which trees are ~ 20 to 30 m tall. It would be necessary to erect a 30 m transmission mast at the southern site.

We anticipate no interference from other radiation sources in the area (personal communication with Pandu Dessai).

1.8.9 Power.

Although solar panels supplied enough power to our temporary sites to run them continuously through the experiment, the cloud cover in the area is occasionally very heavy. For this reason, and because of the existence of power lines near the proposed array, we recommend that the permanent array uses power from the existing high- and medium-(30 KV) voltage lines. On Figure 1-14 we display high (60 KV) voltage power lines in the vicinity of the proposed array. One line runs between Pico de Meirinho and Pico do Gato. It passes to within ~ 500 m of Pico do Gato. The local power company that owns this line estimates it will cost between 25,000 and 30,000 USD to install a new transformer and supply the Pico do Gato facility with 220V power (Pandu Dessai personal communication). Site 5 is located ~ 400 m to the north of the power line. Site 5 could use the same transformer and would just require an overhead line along the north-south road depicted in Figure 1-17. Site 7 is located beneath a power line a short distance from an existing transformer. Loreto (a nearby dairy farm) owns this transformer. A transformer is located at the "Grota Negra" facility located ~ 1000 m to the west of Site 6.

1.8.10 Land Tenure and access.

This is to be determined (see Section 1.8.4). Most of the land at the recommended array location is privately held. According to Pandu Dessai, the Portuguese government owns the land at the southern site. It is extremely unlikely that the local landowners would sell the land. Any arrangement to rent or buy the land would have to involve the local government. We recommend renting the land and reducing the cost of the land rental by deploying "spider" multi-arm space filters in existing hedges or tree-rows. Access to each of the array elements and the central facility is indicated in Figures 1-14 through 1-19. These roads can be expected to be open at all times of the year.

1.8.11 Security.

Security concerns are omnipresent however there is no reason to suspect this is more of a concern at this location than at any of the other stations in the global network. Most activity in this area is relating to the operation of local dairy farms.

1.8.12 Protection from natural hazards and animals.

This site is subject to minimal natural hazards. There is heavy rainfall during the winter season but there is no history of flooding in this area. There is some risk of landslides in the more rugged areas but not at the locations we are recommending for the array. There is an active fault which crosses Sao Miguel approximately 5 km to the west of Cha das Mulas. Occasional swarms of low magnitude earthquakes occur on this fault. The earthquakes can be felt at Cha das Mulas but there is no history of significant damage in this area. A swarm of earthquakes in 1881 caused landslides in the Furnas valley. Cha das Mulas is within the volcanic complex of Achada das Furnas. To the southeast of this area is the Furnas volcanic complex. The last eruption occurred in the Furnas complex in 1630. There is some secondary volcanism in the area. This volcanic activity is well monitored. A recent series of articles on this volcanic complex can be found in a special issue of the Journal of Volcanology and Geothermal Research (Vol 92, 01 Sept, 1999). The text of these papers can be found online at http://www.elsevier.nl/inca/publications/store/5/0/3/3/4/6/.

There are cattle in the area. For this reason we recommend a fence around each noise filter. We recommend that all recording equipment be placed in a shallow fiberglass vault and protected by a fence.

1.8.13 Long term maintenance.

There is considerable technical expertise at the Instituto de Meteorologia, Portugal in Ponta Delgada. Panduronga Dessai and his staff have assisted us throughout our experience in the Azores. We expect that this team would likely be interested in continuing to be involved in the maintenance of the infrasound array.

SECTION 2
THE INFRASOUND SITE SURVEY
CONDUCTED IN CAPE VERDE, WESTERN AFRICA

SUMMARY

This section reviews the results of an infrasound survey that was conducted in Cape Verde, Western Africa near the International Monitoring System (IMS) nominal infrasound site IS11. This survey was conducted to find the location near the nominal site coordinates that would provide the best overall conditions for detecting infrasonic signals of interest above noise and for locating and characterizing the sources. This section summarizes the main elements of the survey - the site selection, the survey, the analysis of the infrasonic noise and meteorological data and our recommendations for the location, configuration and maintenance of the permanent IMS infrasound array.

Following the requirements for a standard survey as outlined by the Provisional Technical Secretariat (Christie, 1998), we conducted a survey of infrasonic noise and meteorological conditions at four points. The sites were chosen after considering meteorological data, topography, vegetation and logistics at sites within 200 km of the nominal infrasound station location. The review clearly indicated that the island of Maio provides the best overall conditions for establishing an infrasound array in this region. The reasons for selecting this location for the survey are as follows:

- Wind: Meteorological data indicate that trade winds are strong throughout the CapeVerde archipelago. The only substantial forest in this country is on the island of Maio. This forest has proven to be effective at reducing local wind speeds.
- Noise: There are very few sources of cultural noise on this sparsely populated island.
- Topography: The western islands in Cape Verde are rugged. Maio is one of the relatively flat eastern islands.
- Security: All sites in the proposed array lie in a state park on Maio. There is a guard posted in the park 24 hours per day. There is little traffic around and in the park.
- Cost: All land required for the proposed array is held by the municipality of Maio.
- Proximity to the nominal treaty coordinates: The exact treaty coordinates are in the
- Atlantic at the center of the archipelago. All islands in the archipelago are approximately the same distance from the treaty coordinates.

- Colocation with seismic: A seismic station in the Incorporated Research Institutions for Seismology Global Seismographic Network (IRIS-GSN) is located ~55 km from the proposed array on the island of Santiago. The location of the seismic station was not chosen for the survey as it is subject to brisk winds and comes with considerable security concerns.

During an 18 day period in January of 1999, infrasonic noise and wind speed, direction, air temperature and humidity data were recorded simultaneously at four sites in the state park on Maio. We analyzed the meteorological and pressure data to characterize the dependence of infrasonic noise on location and on time. Power spectral density was estimated using Welch's method. We observed considerable variability of wind speeds at the four sites. Average instantaneous wind speeds at the four sites ranged from 0.81 to 1.94 m/s. We also observed variable, and sometimes high, infrasonic noise levels although the average noise levels at the four sites were not markedly dissimilar.

We recommend that the state park on the island of Maio be selected as the site of the infrasound array IS11. Having taken into account the infrasonic noise levels and numerous practical constraints we recommend the following:

- An augmented array of 8 elements. We recommend that 5 of the elements be deployed in a 300 m aperture area at the center of the large-scale (2.0 km aperture) array.
- Four of the central elements be equipped with 18 m "multi-port" noise filters. We recommend that one of the inner elements and all outer elements be equipped with 70 m multi-port filters.
- The central recording facility be located near the center of the state park in an existing, and currently unused, building. All proposed sites in the array are to be ocated inside the state park.

2.1 INTRODUCTION.

This section reviews the survey that was conducted by researchers at the University of California, San Diego between the 12th and 30th of January, 1999 to find a good location for the IS11 array in Cape Verde, Western Africa. The survey was conducted in accordance with guidelines described in the Provisional Technical Secretariat (PTS) site survey document CTBT/PCIV/WGB/ 1, Appendix VI.

2.2 ORGANIZATION.

This section reviews all elements of the IS11 site survey including the preliminary site selection, the survey, data analysis, final conclusions and recommendations.

2.3 DESCRIPTION OF THE SURVEY AREA.

The Cape Verde archipelago lies 640 km west of Dakar, Senegal, on the African continent, and east of the mid-Atlantic ridge between latitudes of 15 and 17° N. The archipelago comprises 10 major islands and 5 minor ones (Figures 2-1 and 2-2) which resulted from volcanic activity that occurred 21 1/2 to 65 million years ago. The total land area of the archipelago is 4,033 square km. The largest island, Santiago, covers 991 square km and is roughly 20 by 50 km across. The western islands are relatively young and rugged. The most extreme topographic relief is on Fogo, a 2829 m high active volcano. The central areas of the two largest islands, Santiago and Santo Antao, are very rugged. The highest point on Santiago is ~ 1392 m above sea level. The southwestern parts of Santiago consists of smooth broad plateaus ~ 300 to 400 m above sea level.

These are nearly horizontal basaltic lava flows deeply cut by canyons. The eastern islands, including Sal, Boavista and Maio, are relatively flat. Most vegetation on the Cape Verde islands is found on the upwind (NE) side of the topography. There is typically little rainfall and only sparse vegetation downwind. The islands are arid with an average annual rainfall of ~ 100 mm. Although most vegetation is on the relatively rugged islands, Maio has a substantial Acacia tree forest in a municipality held state park. A government sponsored program for reforestation (primarily Acacia trees) is currently underway on most of the islands. The reforestation effort on Maio was started in 1979 with the intent of extending the existing forest.

The most extensive infrastructure in the country is on Santiago. This island is the site of the capitol city, Praia, and the international airport that connects Cape Verde with the rest of Africa. A second international airport is on Sal and accommodates flights between Cape Verde and Europe and the United States. The Incorporated Research Institutions for Seismology (IRIS) Global Seismographic Network (GSN) station SACV is currently being established on Santiago (Figure 2-2). The nominal location for the IMS infrasound array IS11 is 16.0°N, 24.0°W (Figure 2-2). This point is 115 km from SACV.

The most densely populated islands are Santiago and Santo Antau. Praia, the capital and largest city, has a population of 62,000. Maio is sparsely populated.

The only significant natural hazard in the area is Fogo. Any threat posed by volcanic activity on this island is mitigated by the fact that Fogo lies squarely downwind from Maio and Santiago.

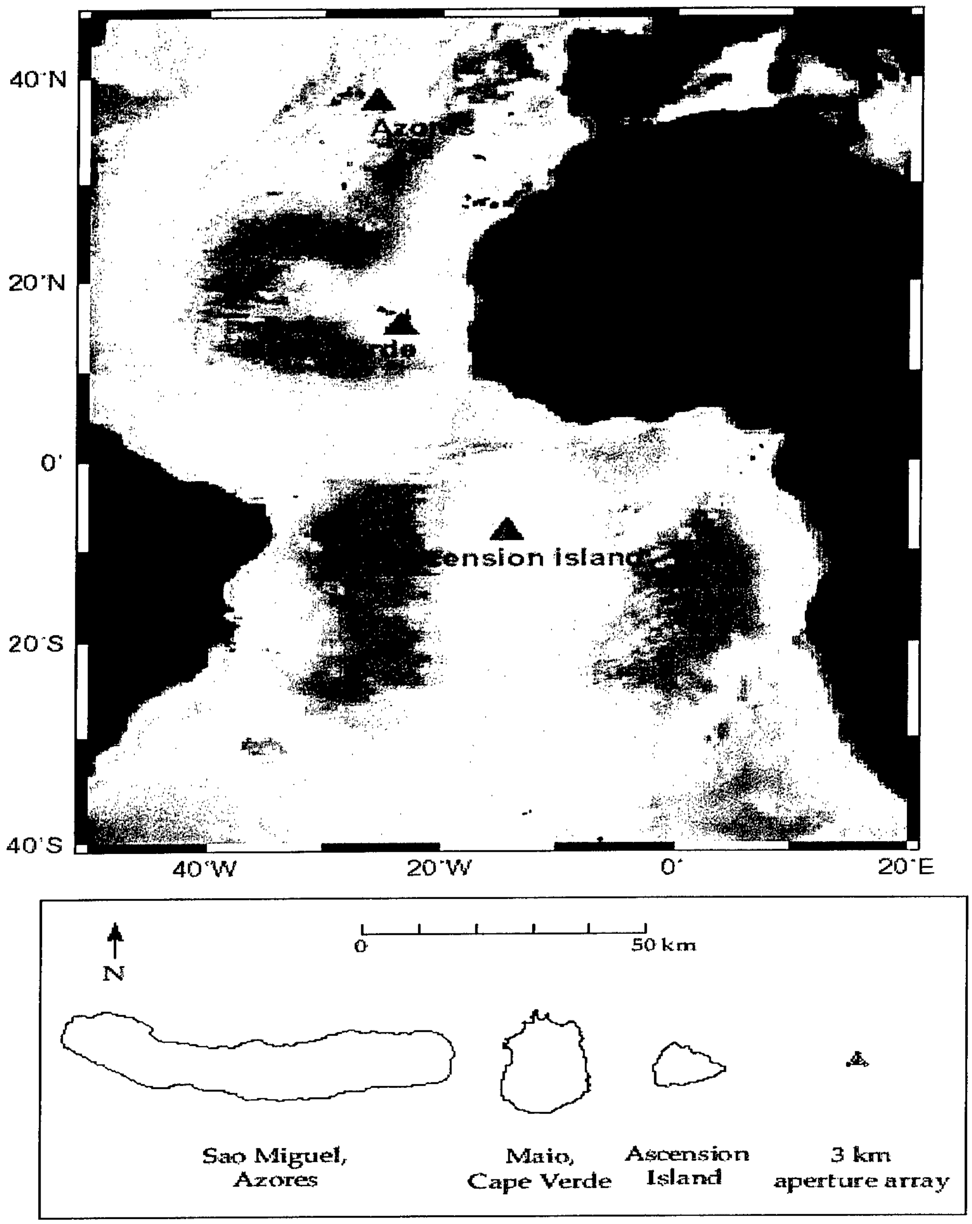


Figure 2-1. Cape Verde is located north of the equator just west of the African continent with the two other sites in the Atlantic which were surveyed by the University of California also shown in the upper panel and the three islands in the Atlantic that we are proposing as sites of future IMS infrasound arrays shown.

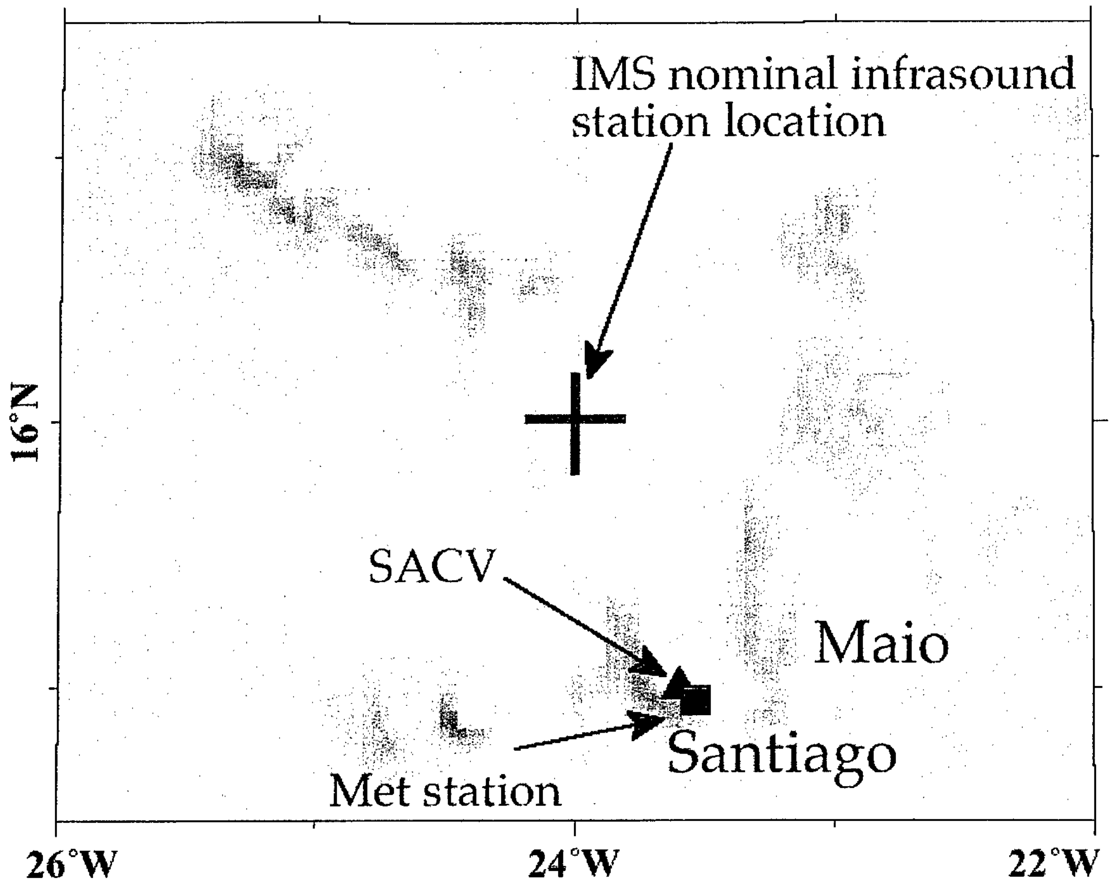


Figure. 2-2. Bathymetry near Cape Verde with the nominal treaty coordinates located at the center of the archipelago, and The GSN station SACV being established on Santiago.

For the reasons given above, most of the islands in Cape Verde do not provide good conditions for establishing an infrasound array or sensing infrasonic signals. The lone exception to this is Maio (Figures 2-2, 2-3 and 2-4) which is sparsely populated, relatively flat and is the site of a significant forest. All four survey sites were located on Maio in the Acacia Tree Forest (Figure 2-5).

2.4 METEOROLOGICAL CONDITIONS

Cape Verde lies in the tropics and has a mild climate. Average annual temperatures range from 20°°C to 25C. The archipelago is subject to unrelenting trade winds from the northeast. Average wind speeds vary from over 5 m/s in the winter to under 2 m/s during the summer. Data from a meteorological station located in Praia (Figure 2-2) shows this seasonal trend and indicates that

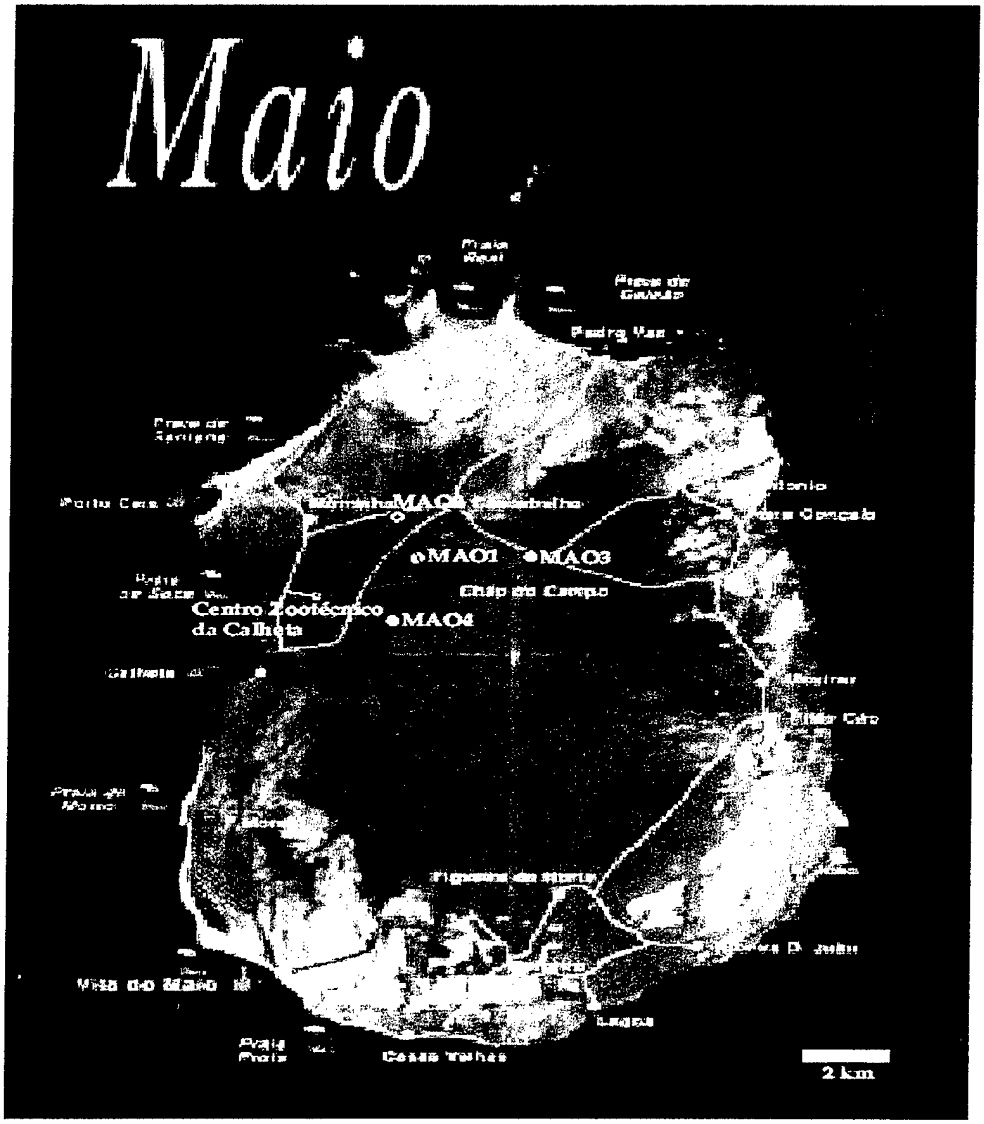


Figure 2-3. The island of Maio, Cape Verde, with the 4 survey points in a forest of Acacia trees identified by the white circles and the recommended array represented by the red triangle [The island has very little vegetation except for an Acacia tree forest in the north, and covers ~ 310 square km - roughly 4 times the size of Ascension Island, the site of another nominal IMS infrasound station].

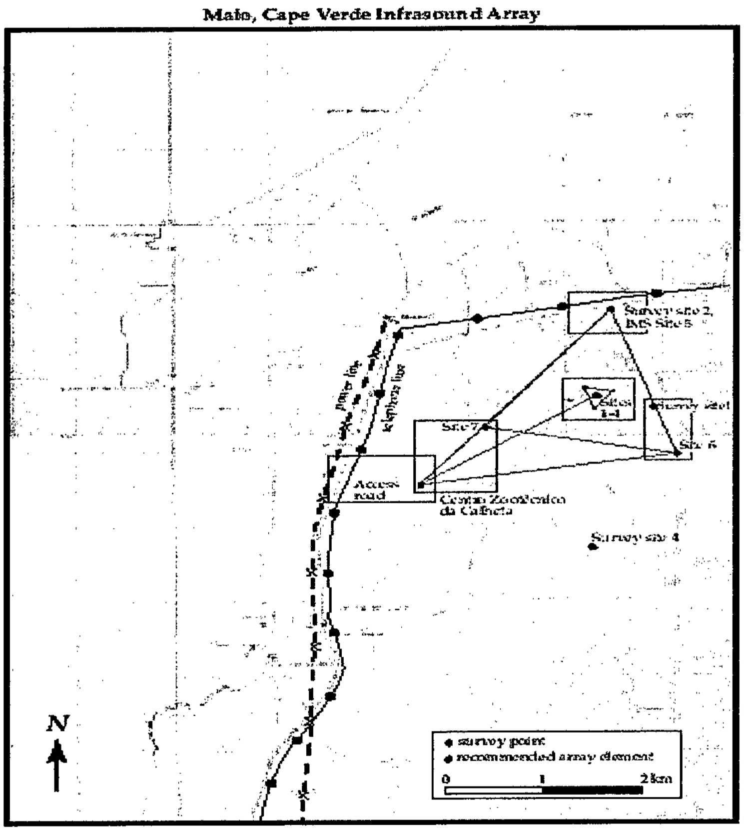


Figure 2-4. Topography and infrastructure on Maio with three of the survey sites indicated by the red symbols, the recommended configuration for the future IMS array indicated by the red triangle, and all space filters shown in black and plotted to scale. [The boxes indicate the areas shown in Figures 2-14 through 2-17].

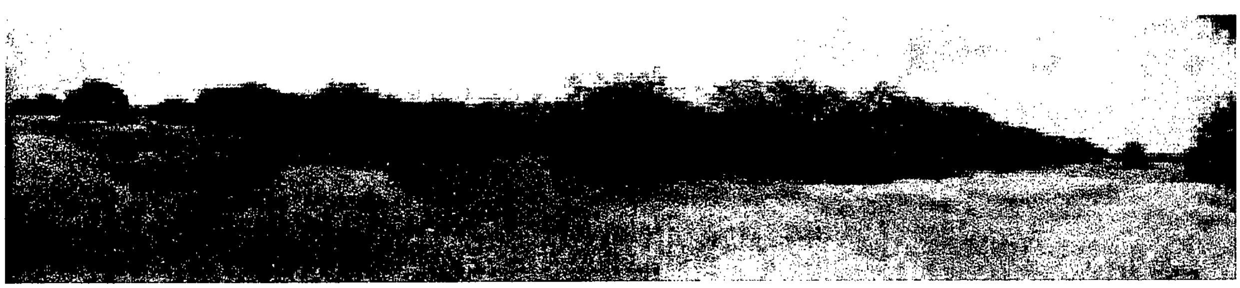


Figure 2-5. A panorama of the eastern edge of the Acacia forest on Maio.

winds are usually stronger in Cape Verde than at Ponta Delgada in the Azores (lowest gray curve in Figure 2-6). The trade winds blow persistently from the N-NE.

2.5 SITE SELECTION.

The meteorological data, together with land ownership ground cover, topography and infrastructure maps, guided us in our selection of survey sites. We considered sites on all islands in the archipelago and have concluded that Maio provides the best conditions for an infrasound array in this area. The reasons for this conclusion are listed below:

- Wind: Meteorological data indicate that trade winds are strong throughout the Cape Verde archipelago. The only substantial forest in this country is on the island of Maio. This forest has proven to be effective at reducing local wind speeds.
- Noise: There are very few sources of cultural noise on this sparsely populated island.
- Topography: The western islands in Cape Verde are rugged. Maio is one of the relatively flat eastern islands.
- Security: All sites in the proposed array lie in a state park on Maio. There is a guard posted in the park 24 hours per day. There is little traffic around and in the park.
- Cost: All land required for the proposed array is held by the Municipality of Maio.
- Proximity to the nominal treaty coordinates: The exact treaty coordinates are in the Atlantic at the center of the archipelago. All islands in the archipelago are approx. the same distance from the treaty coordinates.
- Colocation with seismic: A seismic station in the Incorporated Research Institu tions for Seismology Global Seismographic Network (IRIS-GSN) is located ~ 55 km from the proposed array on the island of Santiago. The location of the seismic station was not chosen for the survey as it is subject to brisk winds and comes with considerable security concerns.

2.5.1 Site 1.

This site was located near the eastern edge of the forest on Maio (Figures 2-3 and 2-4). The Acacia trees in this area are relatively mature and ~ 6 m tall but are broadly spaced.

2.5.2 Site 2.

This location is in a relatively dense part of the Acacia forest just south of the main road (Figure 2-4).

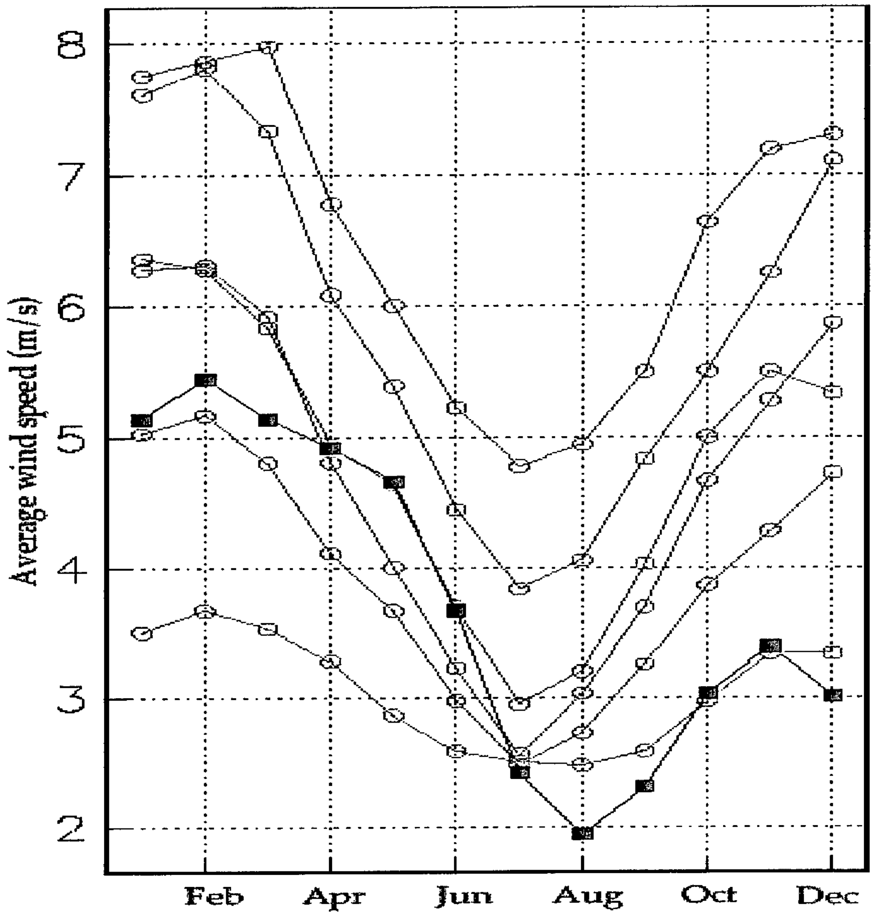


Figure 2-6. Meteorological observations made at Praia taken from a 30 year study (O Clima de Portugal, 1931-1960), are shown above with wind speed data from Praia highlighted in red and compared with observations made in the Azores (grey curves).

2.5.3 Site 3.

This location is in a relatively recent part of the Acacia forest. The trees in this area are less than 10 years old and were planted as part of the reforestation effort (Figure 2-4).

2.5.4 Site 4.

This location is in the southern part of the forest (Figure 2-4).

2.6 EXPERIMENTAL RESULTS.

The 4 survey points on Maio were occupied simultaneously during a 17 day period in January of 1999.

2.7 METEOROLOGICAL CONDITIONS DURING THE SURVEY.

In Figure 2-7 we display wind velocity at the four sites during the survey. These displays are based on 400 estimates of wind speed taken at each site. Each estimate is based on the average wind velocity in a 15 minute period at the beginning of each hour of the experiment. During the survey, the winds were exclusively from the NE. The winds were weakest at the site in the oldest part of the forest (MAO2). The average instantaneous wind speed at this site during our survey was 0.81 m/s. The average wind speeds at the other sites ranged from 1.33 to 1.94 m/s.

2.8 POWER SPECTRAL ANALYSIS METHOD.

All field data were downloaded from the Reftek disks and placed in CSS3.0 format databases. To examine the spectral content of the filtered data we used Welch's method (Welch, 1967) which yields a single power spectral estimate from an average of several taken at regular intervals in the time range of interest. The spectral estimates we have used in this study were derived from an average of 4 estimates, each taken from consecutive 204.8 s intervals. The power spectral estimates were obtained using the Matlab routine "PSD".

2.9 NOISE LEVELS AT THE SURVEY SITES.

Fifteen minutes of pressure and meteorological data from the Cape Verde experiment are shown in Figure 2-8. The unfiltered pressure time-series from the station at site 1 exhibits an integration of short and long-period fluctuations. The shorter period variations dominate the filtered record (second panel). In this time period, minor wind velocity fluctuations are constant. The temperature and humidity vary relatively slowly. The detailed structure of the filtered pressure record results from the superposed contributions of myriad atmospheric phenomena. Our study is concerned primarily with the dependence of the noise on frequency and the exact location of the sensor and thus we will focus on the spectral properties of the noise.
The power spectral density taken from the filtered record (Figure 2-9) shows a decay in power levels from the peak at 30 s to the corner of the anti-aliasing filter at 9 Hz. The microbarom peak is not seen in this time interval.

From the full 17 days of recording at all 4 sites we calculated power spectral density at 400 time intervals. Each interval began at the turning of the hour and lasted for 15 minutes (such as the interval displayed in Figure 2-8). Tenth, 50th and 90 percentile noise levels at all frequencies from 0.005 Hz to 10.0 Hz are shown in Figure 2.- with the minimum and maximum power

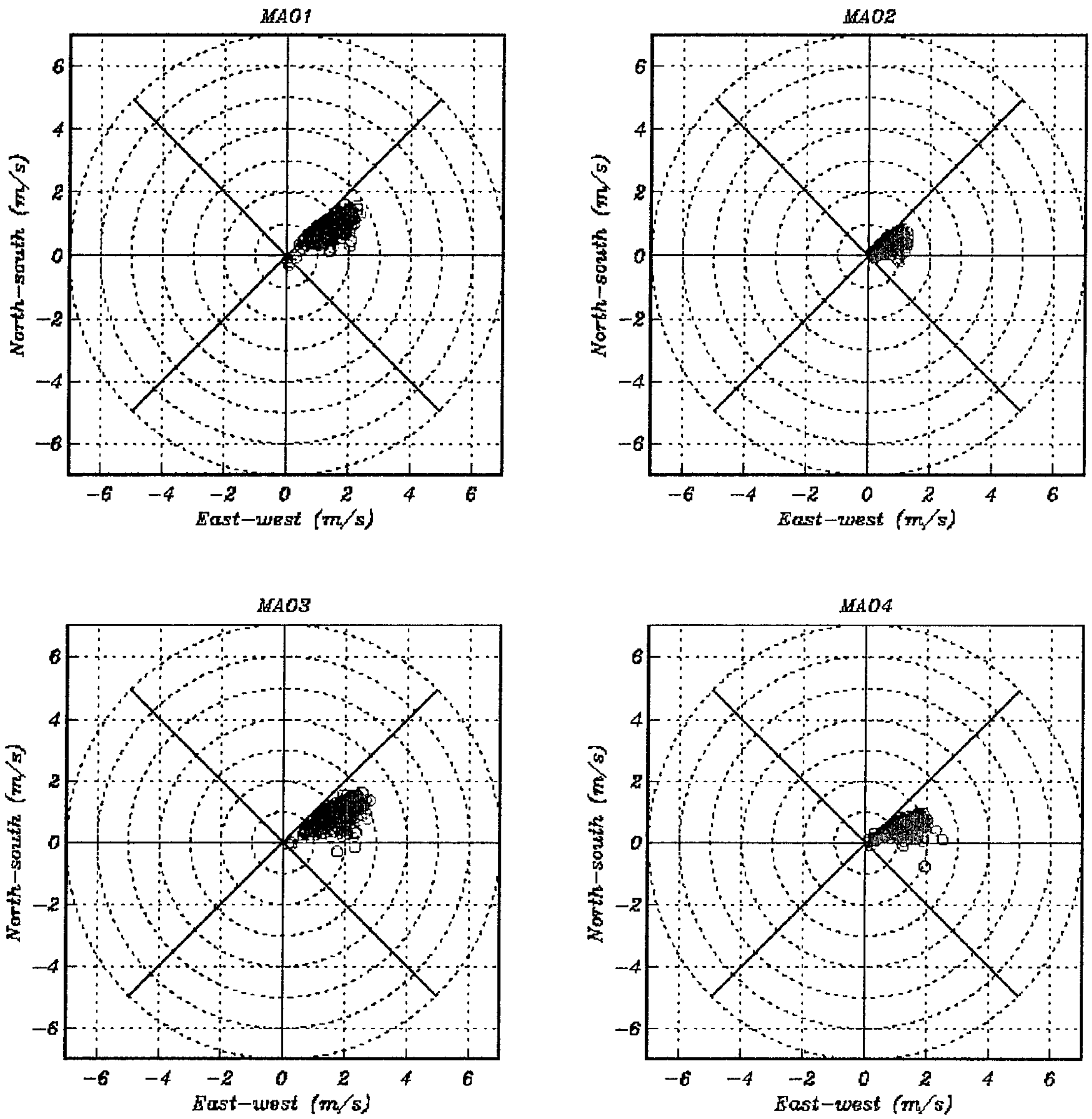


Figure 2-7. Wind velocity at the four sites with wind usually coming from the northeast at the time of the survey.

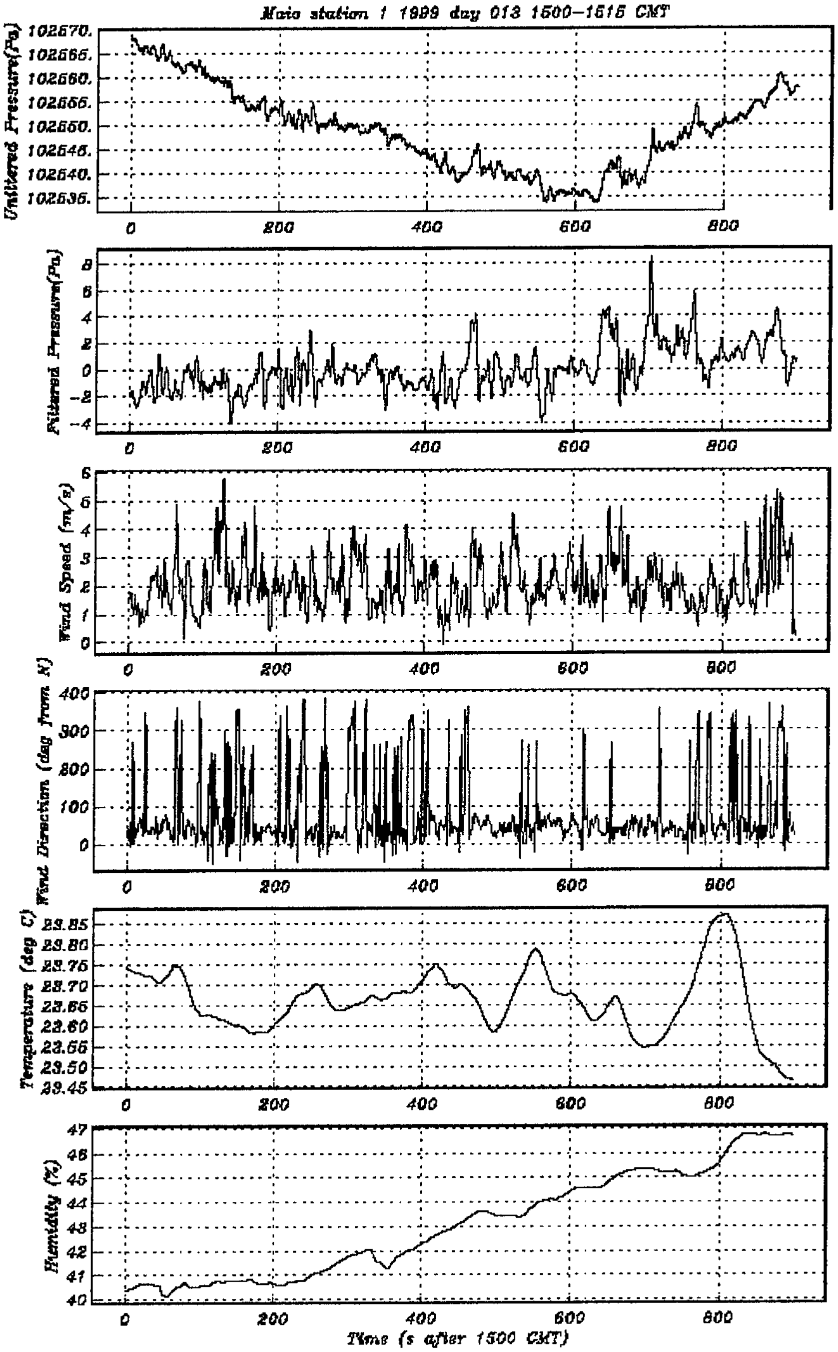


Figure 2-8. Atmospheric pressure and meteorological data during a 15 minute interval on day 13, 1999, with raw and filtered pressure data shown in the upper two panels, and wind speed, direction, temperature and humidity shown below.

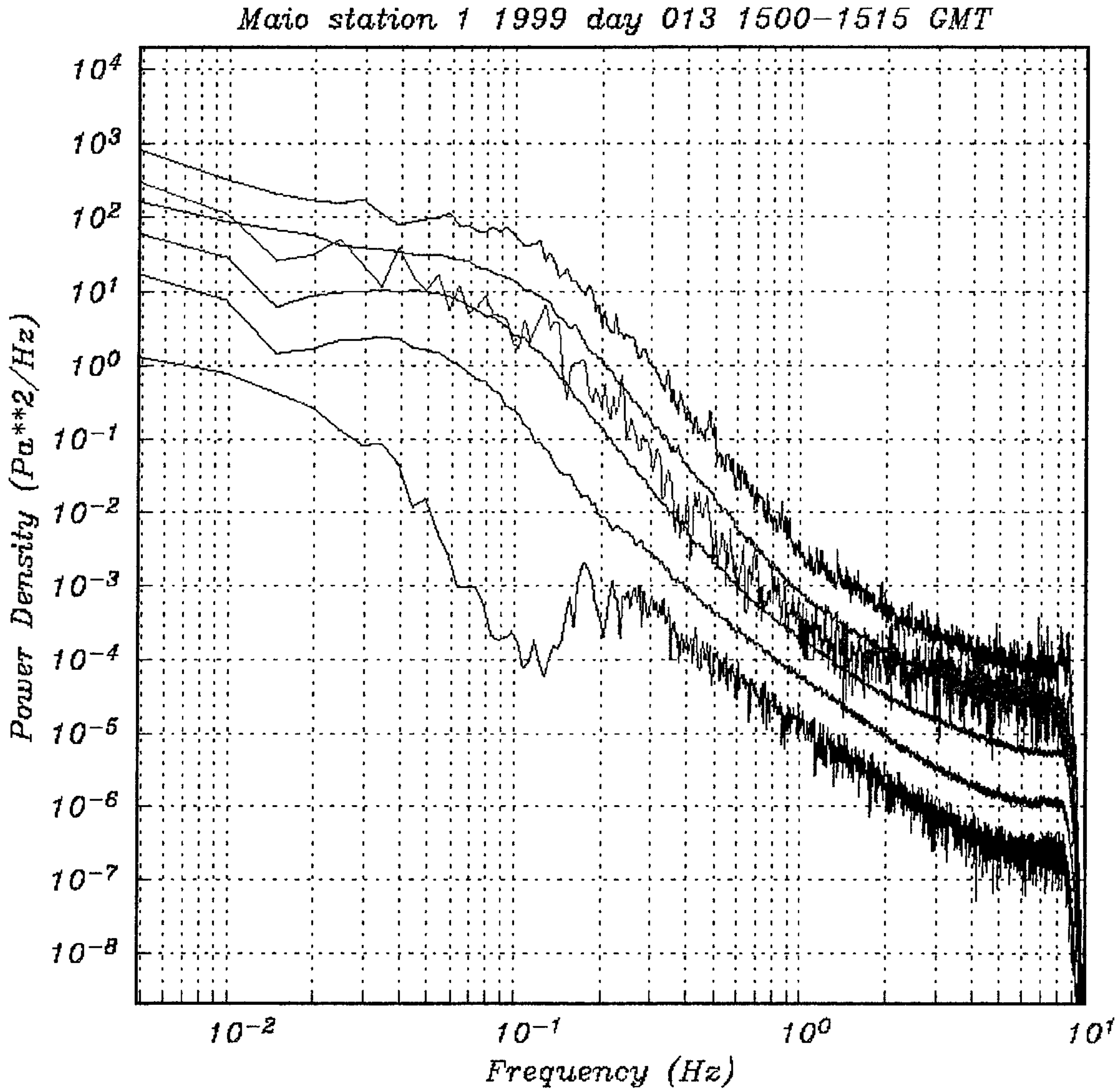


Figure 2-9. A time averaged (Welch) spectrum (in red) and minimum, 10th, 50th and 90th percentile and maximum noise curves from site 1, with the lowest and uppermost curves being the minimum and maximum noise levels observed at this site during the 3 weeks of the experiment and each estimate taken from 15 minutes of data.

levels. At times of relatively low noise the microbarom peak is obvious at site 1. This figure shows that the interval displayed in Figure 2-8 was a time of near-average noise levels.

The same spectral character is seen at all four sites (Figure 2-10). The microbarom, which is clearly seen at times of low infrasonic noise, is only rarely seen at any of the sites. With the exception of high-frequency noise levels seen in one time interval at Site 1, the noise levels at the four sites are very similar.

Infrasonic noise levels on Maio are compared with those observed at 4 other IMS infrasound array locations in Figure 2-9 in Section 1. At frequencies below 0.2 Hz, median noise levels at Maio are 5 to 10 dB higher than median noise levels observed in the Azores and Ascension island in the south Atlantic. Median noise levels on Maio are 5 to 30 dB higher than those observed at Newport, Washington and the Pinon Flat Observatory in California.

As expected, the noise power in the band between .005 Hz and 10 Hz is highly dependent on wind speed. In Figure 2-11 we display the power spectral density at several frequencies between .02 and 5 Hz as a function of wind speed. At times of weak winds the infrasonic pressure levels are very low. Minimum power density levels of 1×10^{-6} Pa^2/Hz are seen at frequencies between 1 and 10 Hz. Infrasonic power levels at long periods (20 s) varied by 35 dB during the experiment. The wind speeds depend strongly on the site. Wind speeds are clearly reduced in the thick forest at Site 2 however there is no obvious reduction in infrasonic noise levels at periods greater than 5 to 10s. The frequency at which the noise reduction becomes apparent depends on overall noise levels (Figure 2-10). We see a noise reduction of ~ 10 dB at 1 Hz and higher at peak wind conditions.

2.9.1 Temporal Variations in Noise Levels.

We observed no significant changes in wind speed and noise levels during our 17 day experiment. Diurnal variations in wind speed and in noise levels at all frequencies are clearly seen (Figure 2-12).

2.10 OBSERVED INFRASONIC SIGNALS.

We were unable to find a coherent high-frequency signals recorded across the temporary deployment in January, 1999. The temporary stations were spread out across an area > 3 km across. This is one reason why we are recommending a smaller, 2 km aperture, 8 element array for Cape Verde. Highly coherent, long period, signals are always seen at times when the wind speeds are low (local night). One example of coherent, long period, waves (presumably acoustic gravity waves) are shown in Figure 2-13).

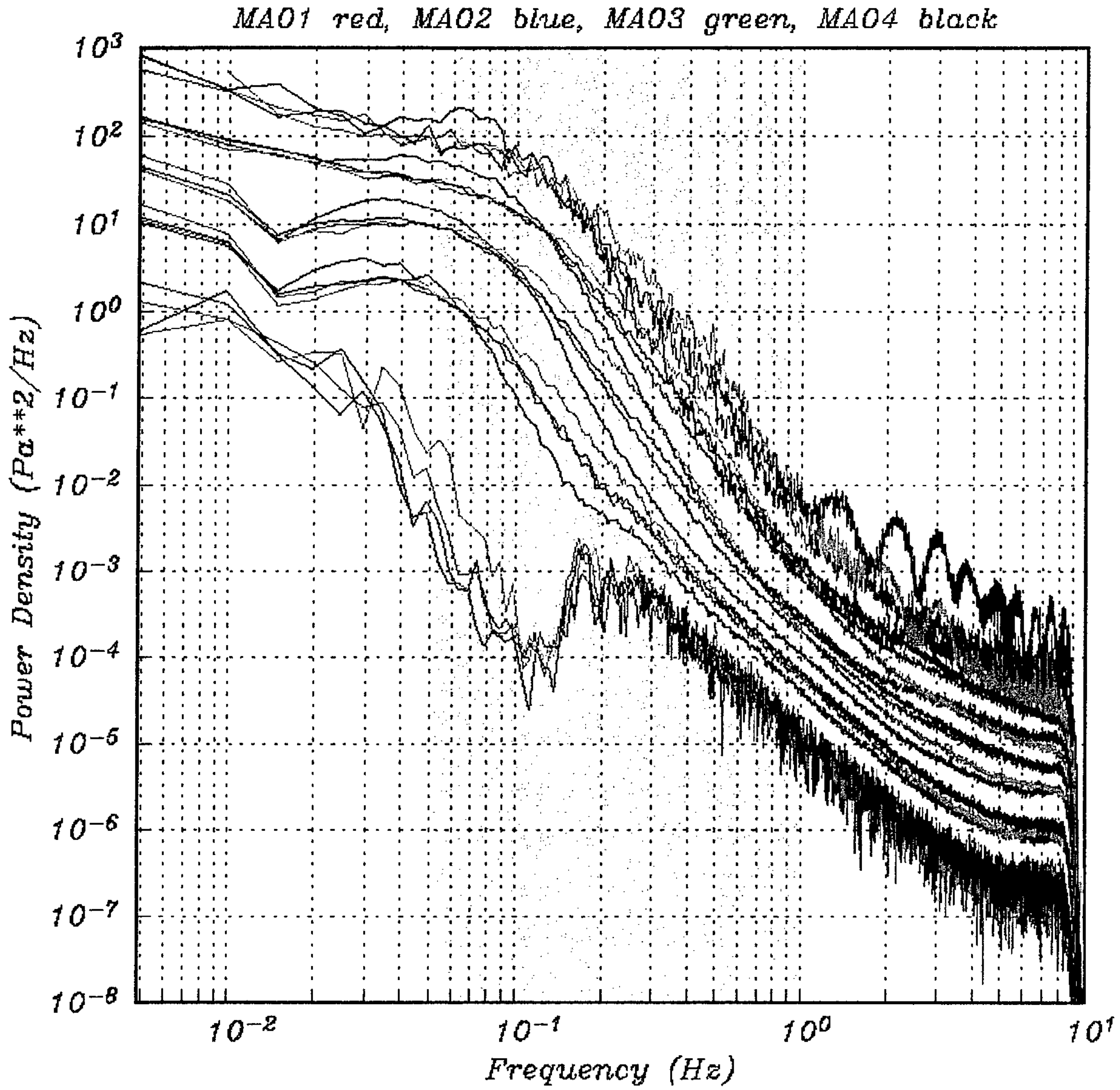


Figure 2-10. The three inner curves are the 10th, 50th and 90th percentile noise levels at the 4 sites and the lower and upper curves are the minimum and maximum noise levels respectively at the 4 sites during the 3 week experiment, with the band of greatest interest to the monitoring community shaded.

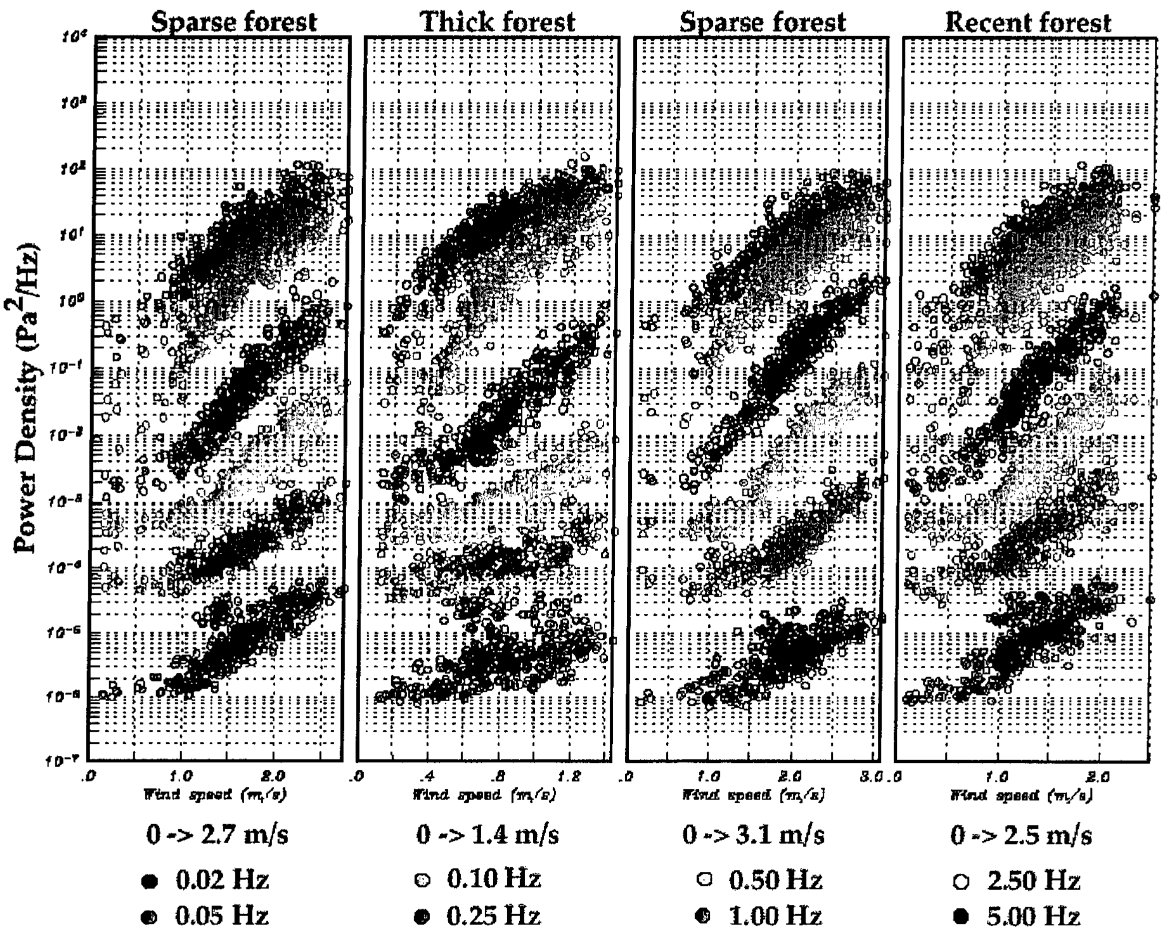


Figure 2-11. Dependence of infrasonic noise on wind speed and frequency at the four sites at PFO, with, from top to bottom in each panel, noise power at 0.02 Hz (black); 0.05 Hz (red) 0.1 Hz (green); 0.25 Hz (dark blue); 0.5 Hz (light blue); 1.0 Hz (pink); 2.5 Hz (yellow); and 5.0 Hz (black).

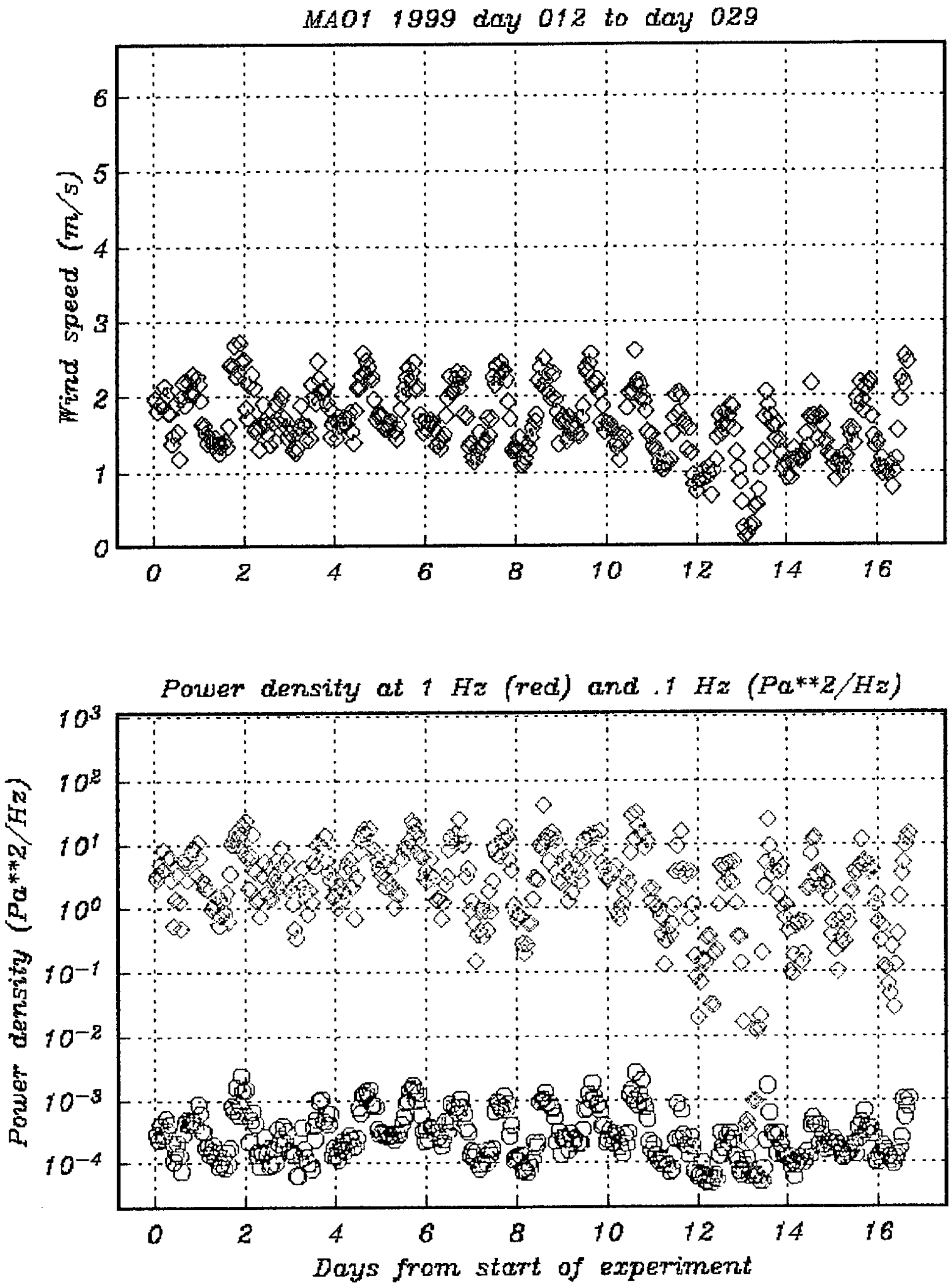


Figure 2-12. Noise power and wind speed as a function of time at station 1, with wind noise at 0.1Hz (upper sequence of points in the lower panel) and at 1.0 Hz tracking closely the wind speed. Strong diurnal variations in the wind speed, and infrasonic noise levels,are evident, and wind speeds are not instantaneous but are average wind speeds during a 15 minute interval which the noise power was estimated.

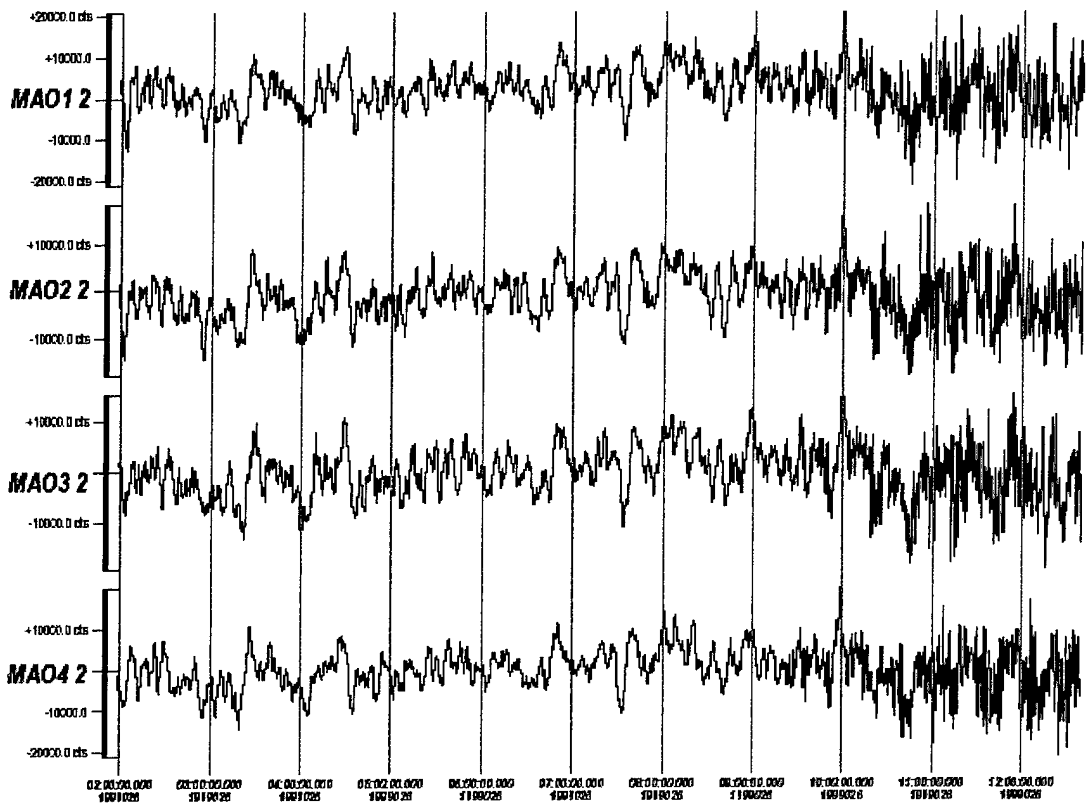


Figure 2-13. This example of highly coherent long period signals recorded during the Cape Verde survey was taken from Jan 25-26, 1999 with the data band passed to 100 s and longer.

2.11 CONCLUSIONS AND RECOMMENDATIONS.

The principal conclusions of this report are the location and the configuration of the infrasound array we are recommending for Cape Verde. These points are discussed in Sections 2.11.1, 2.11.3 and 2.11.4. Also, we discuss the validity of the survey results in Section 2.11.2. In Sections 2.11.5 through 2.11.11 we discuss the expected performance of this array and the logistics of establishing and maintaining the infrasound array.

2.11.1 Determination of the most suitable site.

The primary objective of this field program is to identify the location near the nominal coordinates of IS11 that is most suitable for a permanent IMS infrasound array. The paramount factor is infrasonic noise however our selection must be guided by practical considerations. A site that offers low infrasonic noise but gives few options for siting a permanent array might not be optimal. The ideal site is large enough to allow any array configuration from 1 to 3 km aperture to be considered. In Cape Verde, one site that can accommodate an infrasound array of any dimension is Maio.

A careful review of meteorological data collected at several sites on Maio indicates that wind speeds at all areas can be expected to be high, on average. The data analysis indicates that the kind of vegetation found in the forest on Maio will reduce wind speeds by up to 50% however infrasonic noise levels at periods greater than 5 to 10s are not depressed substantially.

Having considered the meteorological and infrasound data, and having considered the points listed in Section 2.5, we have concluded that the best option for the IMS infrasound array IS11 is in the state park on Maio. This was the site at which all of the measurements were made.

Our survey indicates that modest (~ 5 dB) noise reduction is seen in the band of interest to the monitoring community at the site in the dense forest (Figure 2-10). The 'old' part of the forest that includes Site 2 is large enough to accommodate an infrasound array of 2-3 km aperture. Our brief survey indicates that this area is not subject to substantial noise level swings (Figure 2-12) however diurnal noise level changes are omnipresent. Any infrasound monitoring station located in the region will offer a sensitivity that depends strongly on the time of day. As shown in Figure 2-6, our survey was conducted at a time of relatively high winds.

2.11.2 Validity of Survey Results.

Because of limited resources and manpower, this infrasound site survey lasted 17 days. This gives just a glimpse of the full range of meteorological conditions that will occur in a typical year. Is it fair to assume that the brief period sampled is representative of the entire year and the survey will allow us to recommend the best site or is a 2 to 3 week survey too brief to be useful?

For a brief survey to be ineffective, climactic conditions at the time of the survey would have to be out of the ordinary and tilt the balance of infrasonic noise so that the relative noise levels at the sites are not representative of the yearly average. Intuitively, this seems rather unlikely and easy to check. The chief source of infrasonic noise is turbulence due to wind flow over topography. If wind direction changes in such a way that the wind-topography interaction at the time of the survey is unusual and, as a result, anomalously little turbulance is generated at certain sites, or excessive turbulence is generated at others, the brief survey taken at that time would be misleading. It should be possible to rule out this scenario by comparing wind velocity measurements made during the survey with those from long-term meteorological observations. A significant discrepancy in wind speed or direction combined with azimuthally dependent topography would be cause for concern. The trade winds observed during the survey appear to be consistent with long term observations.

2.11.3 Proposed Permanent Array Configuration.

The surveys are to consider infrasound arrays with apertures between 1 and 3 km. Large arrays permit more accurate estimates of the back azimuth of infrasound sources but require highly coherent signals. Smaller arrays have poorer resolution however are preferred at locations where signal coherence is poor. At sites where noise, most notably the microbarom, is highly coherent, larger offsets between array elements might be required. Due to the presence of high noise due to winds, the modest noise reduction observed in the forest at high frequencies, because of the lack of coherent high frequency signals at broad spacings during the survey, and because of size of the forest on Maio, we are recommending an array with an aperture of ~ 2.0 km. Although the standard IMS array is to include just 4 sensors, we believe that the ambient wind conditions and overall noise levels in the region are high enough so that adequate array performance will require an augmented array of 8 elements. The preferred array is depicted in Figure 2-4. This array includes 5 elements in a central area ~ 300 m across.

GPS coordinates of the array sites and the central processing facility (CPF) are given in Table 2.1. Sites 1 through 4 are in the inner, high-frequency optimized, array. Sites 5,6 and 7 are in the outer, long-period, array. We propose both short-period and long-period elements at Site 1.

Table 2-1 Recommended coordinates of elements in infrasound array.

	Latitude (°N)	Longitude (°W)	Elevation (m)
Site 1.	15° 15.42′	23° 11.12′	8
Site 2.	15° 15.49′	23° 11.18′	8
Site 3.	15° 15.33′	23° 11.15′	8
Site 4.	15° 15.44′	23° 11.02′	8
Site 5.	15° 16.03′	23° 11.04′	9
Site 6.	15° 15.01′	23° 10.66′	22
Site 7.	15° 15.20′	23° 11.76′	11
CPF	15° 14.81′	23° 12.10′	10
GCI VSAT	15° 14.81′	23° 12.10′	10

All of these sites are located on land held by the municipality of Maio. The proposed array is located 120 km from the treaty coordinates. Photos and detailed drawings of these sites are shown in Figures 2-14 through 2-18.

Signal blockage in this area is not an issue. Likewise, turbulence from air flow off nearby topography should not be a serious consideration. With the exception of some horizon blockage caused by small nearby hills located to the east, all topography lies below 10° above the horizontal. Most sites see to within 2° of the horizon at virtually all azimuths.

2.11.4 Array response.

The impulse response of the recommended array configuration is shown in Figure 2-19. In this figure, we display the amplitude of the array response at a linear scale. All values are normalized to 1 at the peak of the mainlobe. The impulse reponse has been calculated at wavenumbers between +/- 1.5 cycles/km. These wavenumber limits include acoustic energy at wavenumbers down to that of a 0.5 Hz horizontally propagating wave. The impulse response has several sidelobes at wavenumbers between 0.75 and 1.0 cycles/km. The sidelobes peak at ~70% the amplitude of the mainlobe. The dominance of the mainlobe in this array response calculation is largely due to the addition of extra elements near the center of the array.

2.11.5 Wind-noise reducing space filters.

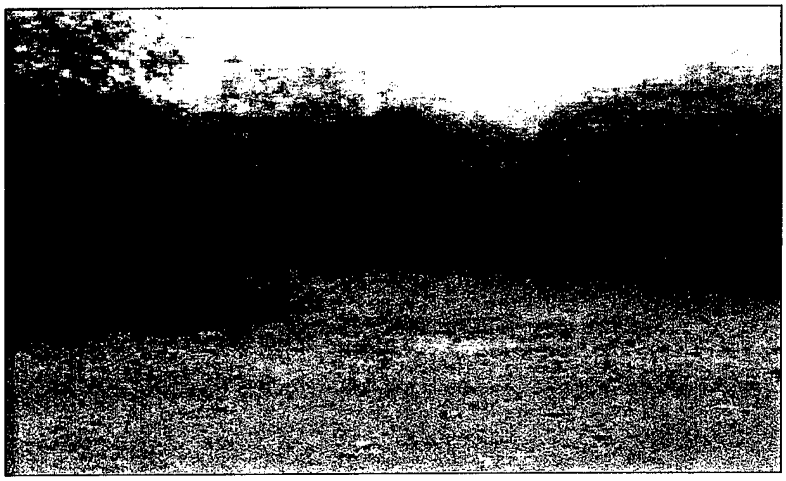
Following the recommendations of the PTS, we believe the most suitable noise filters for this location are the multiport filters discussed in Appendix A. We recommend 70 m aperture noise filters for all outer elements in the array. This should enhance the effectiveness of the outer array for detecting long period (20 s to 1 Hz) signals. We recommend that the stations in the inner 300 m aperture mini-array be equipped with 18 m aperture space filters to improve detection of high-frequency (1 to 4 Hz) signals with one site (site 1) also equipped with a 70 m filter.

2.11.6 Central recording facility.

We recommend that the central recording facility be located in an existing building in the zoological station. The GCI VSAT antenna should be placed beside the building (Figure 2-18).

2.11.7 Communications.

We tentatively recommend hard-wire communications at this array between the elements and the central processing facility. Virtually all the land in the observatory is undeveloped. We recommend trenching the signal cables.



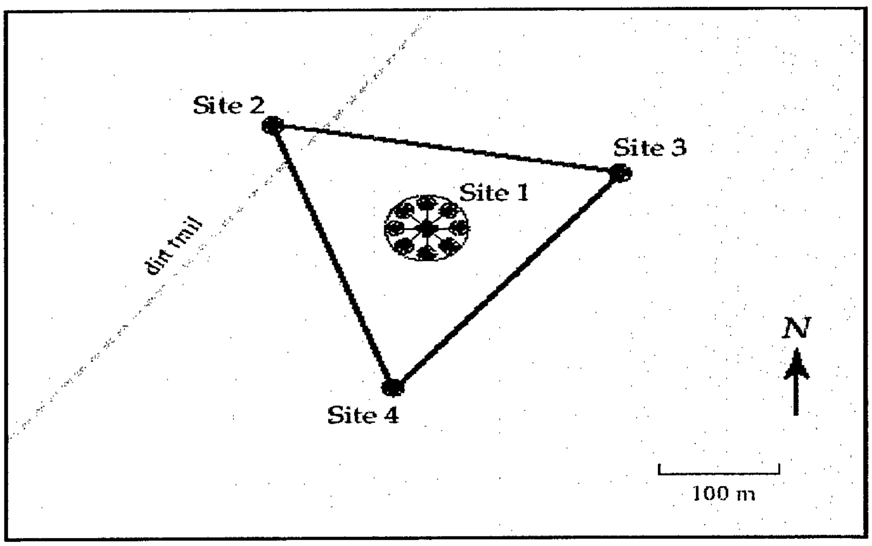
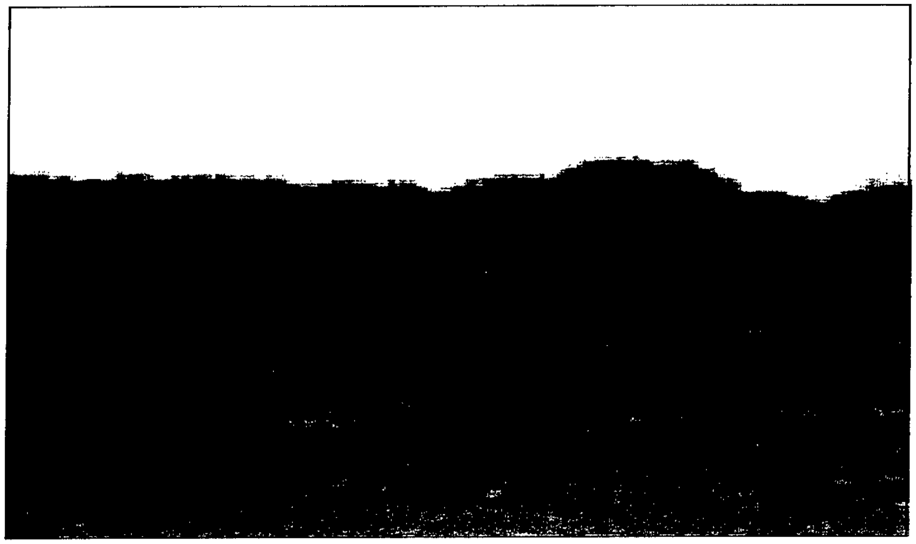


Figure 2-14. Photo and sketch of the central area of the proposed array.



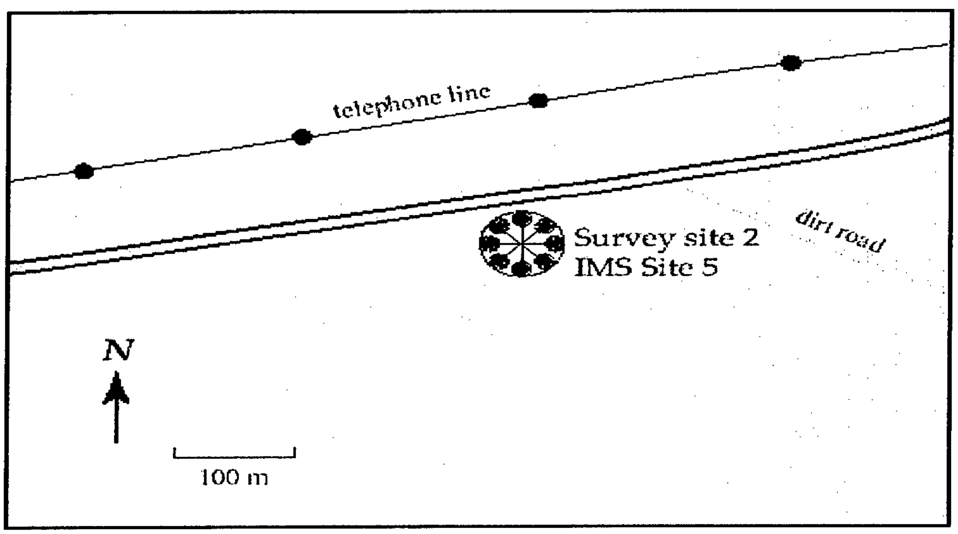


Figure 2-15. A single photo and sketch of IMS Site 5, occupied during the survey (as site MAO2).

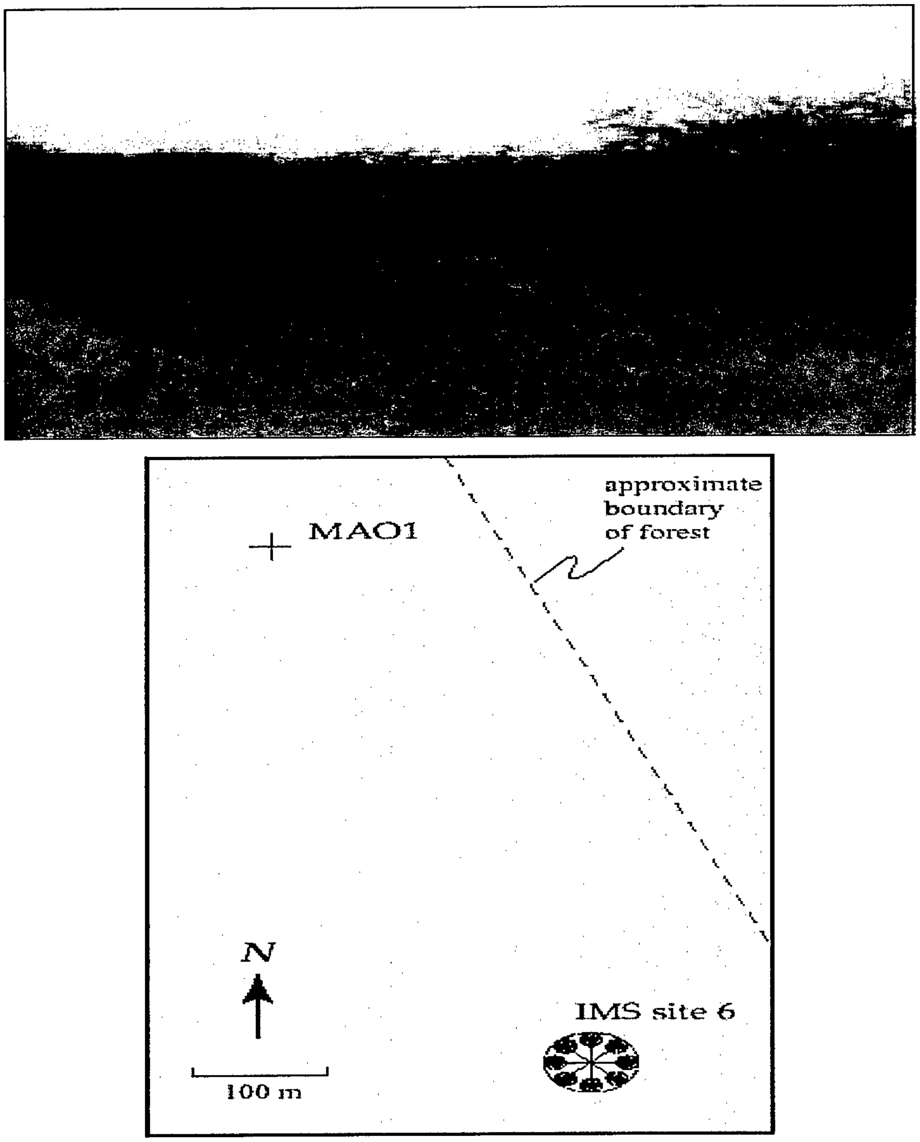


Figure 2-16. A single photo of Site 6, with MAO1 located just to the north of this location.

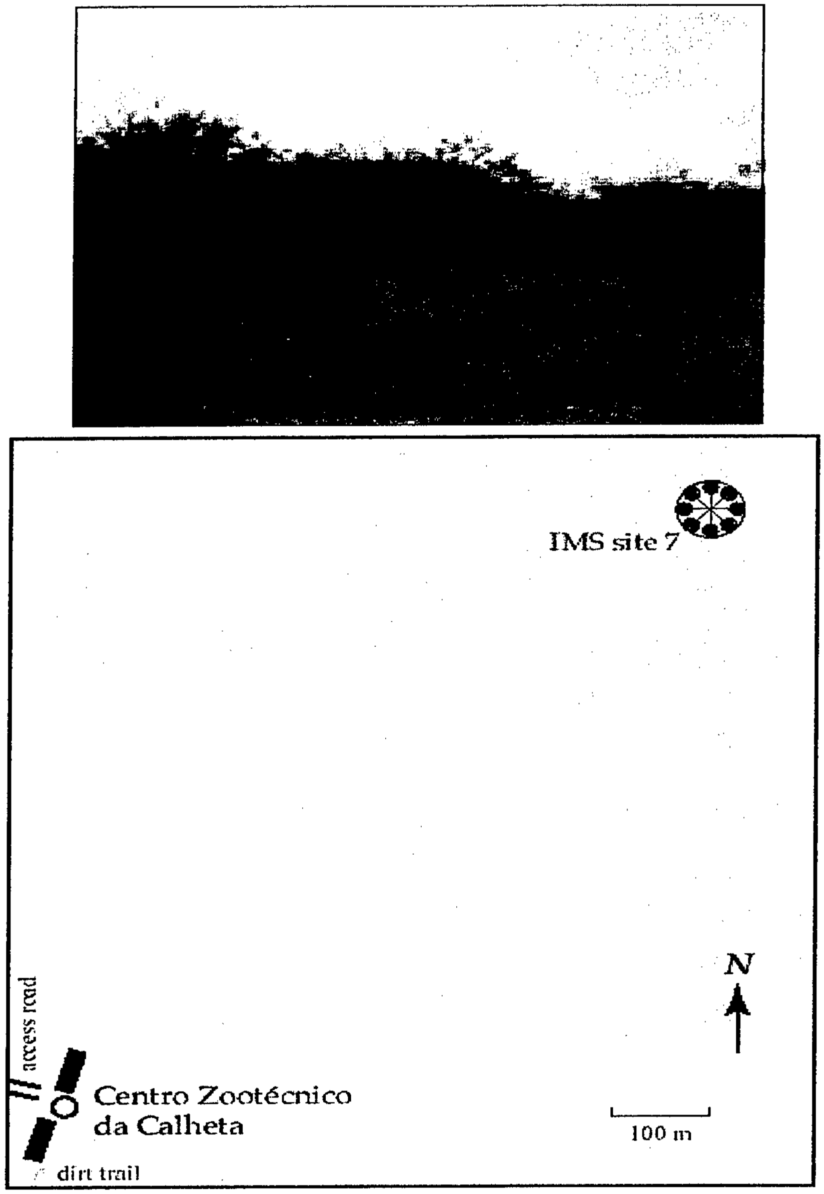
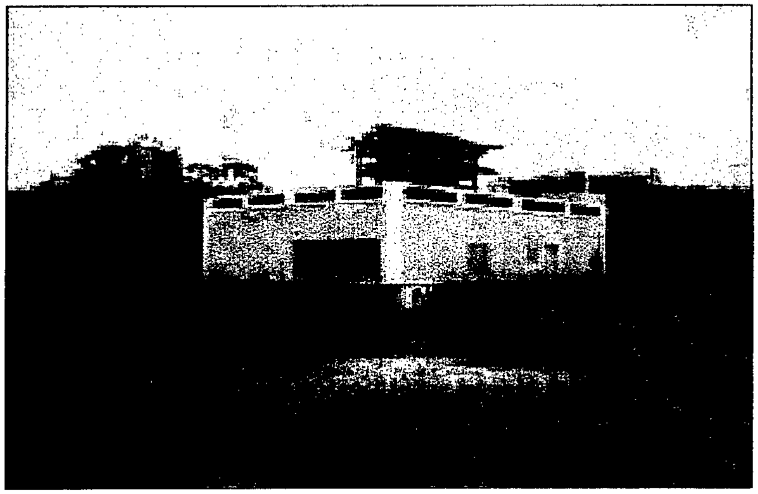


Figure 2-17. A single photo of Site 7.



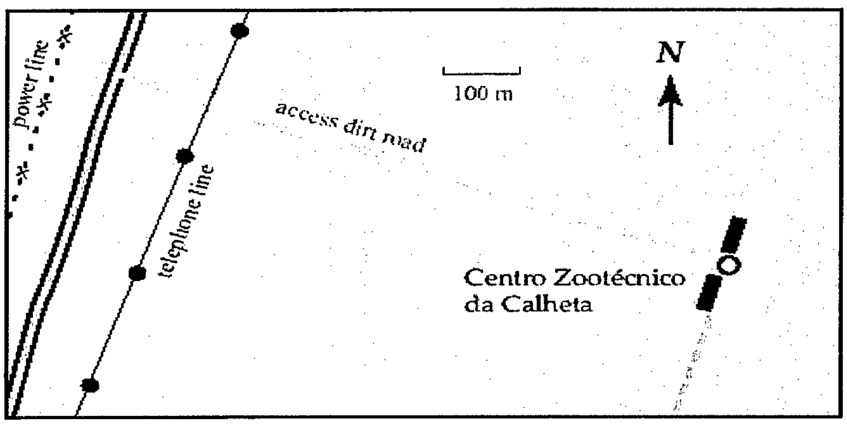


Figure 2-18. We recommend locating the central processing facility in this building at the zoological center.

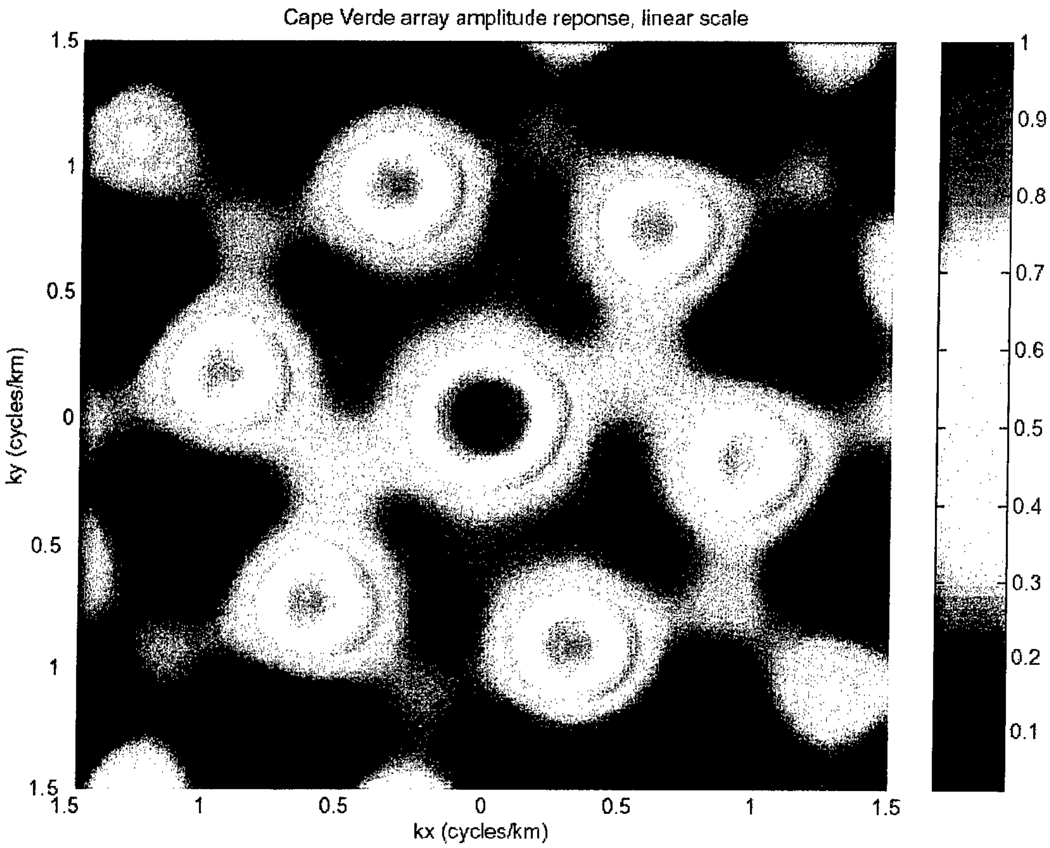


Figure 2-19. Impulse response of the recommended 8 element array on Maio.

2.11.8 Power.

There is existing power supplied to the buildings in the zoological station. We recommend that power cables be placed in the trenches along with the signal cables.

2.11.9 Land Tenure and access.

All sites in the proposed array, including the central processing facility, are located on land parcels held by the municipality of Maio. The land should be made available for a nominal fee after discussions with Manuel Ribeiro, the Mayor of Maio.

2.11.10 Security.

Security concerns are omnipresent however there is no reason to suspect this is more of a concern at this location than at any of the other stations in the global network. The island is sparsely populated. A watchman tours the facility at all hours.

2.11.11 Protection from natural hazards and animals.

This site is subject to no significant natural hazards. Fogo, the active volcano in the country, is located downwind from Maio. There is wildlife in the area and occasional off-road activity. For this reason we recommend a fence be placed around each noise filter and recording equipment vaults.

SECTION 3
THE INFRASOUND SITE SURVEY ON ASCENSION ISLAND

SUMMARY

This section reviews the results of an infrasound survey that was conducted on Ascension island near the International Monitoring System (IMS) nominal infrasound site IS50. This survey was conducted by researchers at the University of California, San Diego to find the location near the nominal site coordinates that would provide the best overall conditions for detecting infrasonic signals of interest above noise and for locating and characterizing the sources. This report summarizes the main elements of the survey - the site selection, the survey, the analysis of the infrasonic noise and meteorological data and our recommendations for the location, configuration and maintenance of the permanent IMS infrasound array. The report includes a summary of the technical specifications and testing of the field equipment.

Following the requirements for a standard survey as outlined by the Provisional Technical Secretariat (Christie, 1998), we conducted a survey of infrasonic noise and meteorological conditions at four points. The sites were chosen after considering meteorological data, topography, vegetation and logistics at all sites on the island. The review clearly indicated that the best overall conditions for establishing an infrasound array in this region lie near the center of the island. This is the only acceptable location on the island as the northern part of the island is covered by rugged basaltic lava flows, the southeast end of the island is very rugged and subject to strong trade winds. The southwest part of the island is relatively heavily populated and is the site of the airfield. Additional reasons for selecting this location for the survey and the permanent deployment are as follows:

- Wind: The trade winds are strong at all points on Ascension island but are relatively weak near the center of the island due to shielding from Green mountain.
- Noise: The center of the island is relatively far from the surf, Wideawake airfield, and Georgetown, the largest town on the island.
- Power: There are several 11 kV power lines in this area.
- Topography: Ascension island is a rugged, volcanic, island. There are large relatively flat areas near the center of the island.
- Cost: All sites in the proposed array lie on British crown land.
- Colocation with seismic: One of the proposed array elements is co-located with the
- Incorporated Research Institutions for Seismology Global Seismographic Network station ASCN.

During a seven week period in March, April and May of 1999, infrasonic noise and wind speed, direction, air temperature and humidity data were recorded simultaneously at four sites on Ascension Island. We analyzed the meteorological and pressure data to characterize the dependence of infrasonic noise on location and on time. Power spectral density was estimated using Welch's method. We observed considerable variability of wind speeds at the four sites. Average instantaneous wind speeds at the four sites ranged from 2.55 to 4.02 m/s. We also observed variable, and often high, infrasonic noise levels although the average noise levels at the four sites were not markedly dissimilar.

We recommend that the center of Ascension island be selected as the site of the infrasound array IS50. Having taken into account the infrasonic noise levels and numerous practical constraints we recommend the following:

- An augmented array of 8 elements. We recommend that 5 of the elements be deployed in a 300 m aperture area at the center of the large-scale (2.5 km aperture) array.
- Four of the central elements be equipped with 18 m "multi-port" noise filters. We recommend that one of the inner elements and all outer elements be equipped with 70 m multi-port filters.
- The central recording facility be located at the Red Lion facility on Green Mountain.
- This location has line-of-site visibility to all of the proposed array elements.

3.1 INTRODUCTION.

A network of 60 infrasound stations is being established as part of the International Monitoring System (IMS) to monitor compliance to the Comprehensive Nuclear-Test Ban Treaty (CTBT). The network includes 23 oceanic stations: one of these (IS50) is to be on Ascension Island. This report summarizes the survey that was conducted by researchers at the University of California, San Diego between March 26 and June 2, 1999 to find a good location for the IS50 array. The survey was conducted in accordance with guidelines described in the Provisional Technical Secretariat (PTS) site survey document CTBT/PCIV/WGB/1, Appendix VI.

3.2 ORGANIZATION.

This section reviews all elements of the IS50 site survey including the preliminary site selection, the survey, data analysis, final conclusions and recommendations.

3.3 DESCRIPTION OF THE SURVEY AREA.

The nominal location for the IMS infrasound array IS50 is 8.0° S, 14.3° W (Figure 3-1). This point is approx. 10 km to the southeast of Ascension Island. Ascension is located in the south Atlantic approx. 1100 km to the northwest of Saint Helena and just west of the mid-Atlantic ridge. The island was discovered on by the Portuguese explorer Joao da Nova Castella on Ascension day in 1501 and is held by the United Kingdom as a dependency of St. Helena. Ascension is a volcanic island that covers ~ 90 sq. km. (Figure 3-2). The island has 44 dormant, but not extinct, volcanic craters. Most of the sub-tropic island is dry and barren and is covered by basaltic lava flows. The most recent volcanic eruption occurred near the center of the island ~ 600 years ago. The most significant peak on the island is Green Mountain (elev 859 m). The upper reaches of the mountain are densely vegetated with a wide variety of tropical plants. The island is home to a number of species of animals, most notably, the green turtle, which uses the island for laying eggs. The island is occupied a variety of small animals including donkeys, sheep, cats, rabbits and mice and a number of species of birds.

There is no indigenous population. Most (~ 70%) of the 1100 people on the island are from Saint Helena and live in Georgetown or Two Boats. The island population includes ~ 200 people from the UK and 150 from the United States. Due to its strategic location, Ascension is a center for telecommunications and is used to provide service to South America and Africa. The British Broadcasting Corporation offshoot, Merlin communications International, is located on the island. The US and British military have facilities on the island.

3.4 METEOROLOGICAL CONDITIONS.

Daytime temperatures at sea level on this sub-tropical island range from 20 to 31□C. The warmest months are March and April with mean monthly minimum and maximum temperatures of 25.0 to 30.5□C. The coolest month is September (21.0 to 25.5□C). Temperatures at the summit of Green are ~5□ lower than most other locations on the island. Rain showers can occur at any time of the year but are heaviest from January to April. Average rainfall varies from 8.0 mm in Oct to 59.3 mm in April. The island is located in the southern trades and is subject to strong winds from the southeast (Figure 3-3). Winds are strongest at the southeast shore of the island. Winds are relatively weak downwind of Green Mountain. In Georgetown median wind speeds vary from 1.5 to ~2.5 m/s (Figure 3-4).

3.5 SITE SELECTION.

The meteorological data, together with ground cover, topography and infrastructure maps, guided us in our selection of survey sites. We considered sites at all points on the island and have concluded that the area near Travelers Hill provides the best conditions for an infrasound array in this area. The reasons for this conclusion are listed below:

- Wind: The trade winds are strong at all points on Ascension island but are relatively weak near the center of the island due to shielding from Green mountain.
- Noise: The center of the island is relatively far from the surf, Wideawake airfield and Georgetown, the largest town on the island.
- Power: There are several 11 kV power lines in this area.
- Topography: Ascension island is a rugged, volcanic, island. There are large relatively flat areas near the center of the island.
- Cost: All sites in the proposed array lie on British crown land.
- Colocation with seismic: One of the proposed array elements is co-located with the Incorporated Research Institutions for Seismology Global Seismographic Network station ASCN.

3.5.1 Site 1.

This site was located near the center of the island just north of Travellers Hill (Figure 3-5).

3.5.2 Site 2.

This site was located at the east end of the One Boat golf course (Figure 3-5).

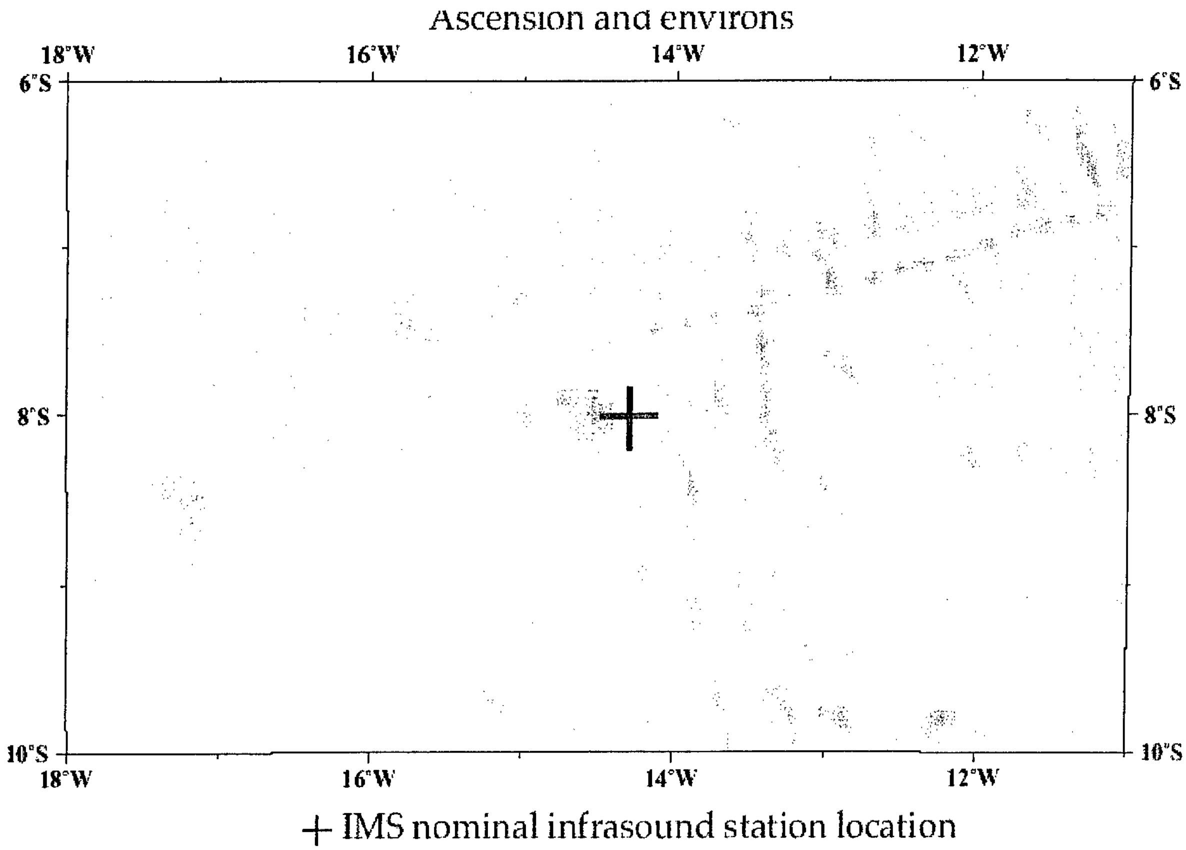


Figure 3-1. Bathymetry near Ascension island with the nominal treaty coordinates just offshore.

3.5.3 Site 3.

This site is near Donkey Plain (Figure 3-5).

3.5.4 Site 4.

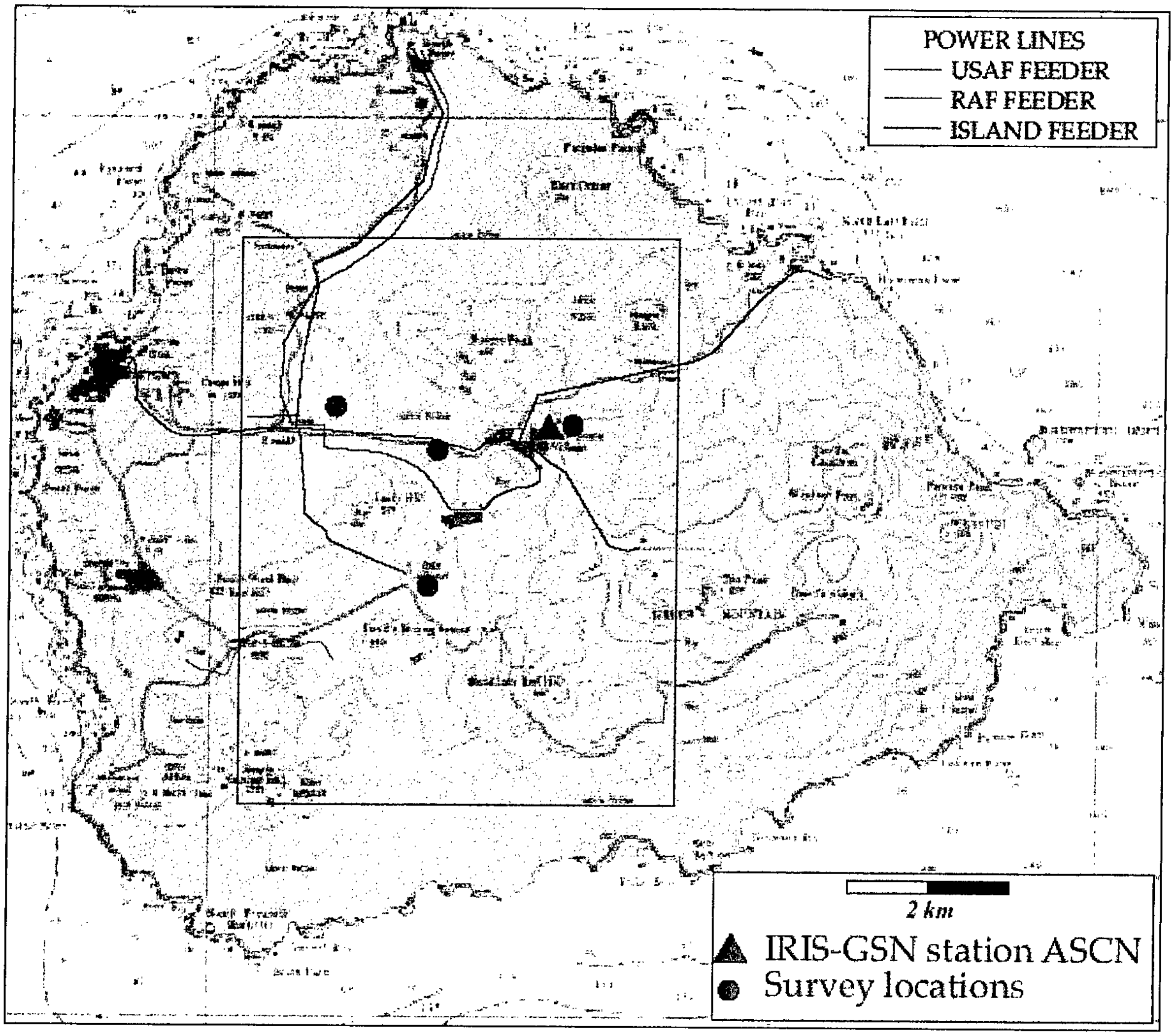
This site is in Butt Crater on the Green mountain flood plain adjacent to the GSN station ASCN (Figure3-5).

3.6 EXPERIMENTAL RESULTS.

The 4 survey points at Ascension island were occupied for a 68 day period between mid-March and early June of 1999. Recording that was simultaneous at all four sites spanned a 33 day period at the beginning of the experiment.

3.7 METEOROLOGICAL CONDITIONS DURING THE SURVEY.

In Figure 3-6, we display wind velocity at the four sites during the survey. These displays are based on 705 estimates of wind speed taken at each site. Each estimate is based on the average wind velocity in a 15 minute period at the beginning of each hour of the experiment. During the survey, the winds were predominantly from the SE. The winds were weakest at the central site. The average instantaneous



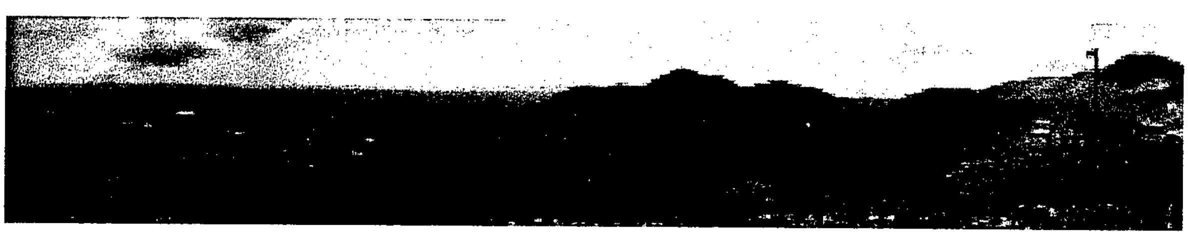


Figure 3-2. Topography on Ascension Island the survey sites being all located near the center of the island, and a panorama of north-central Ascension island taken from Lady Hill showing a recent lava flow near the center of the image.

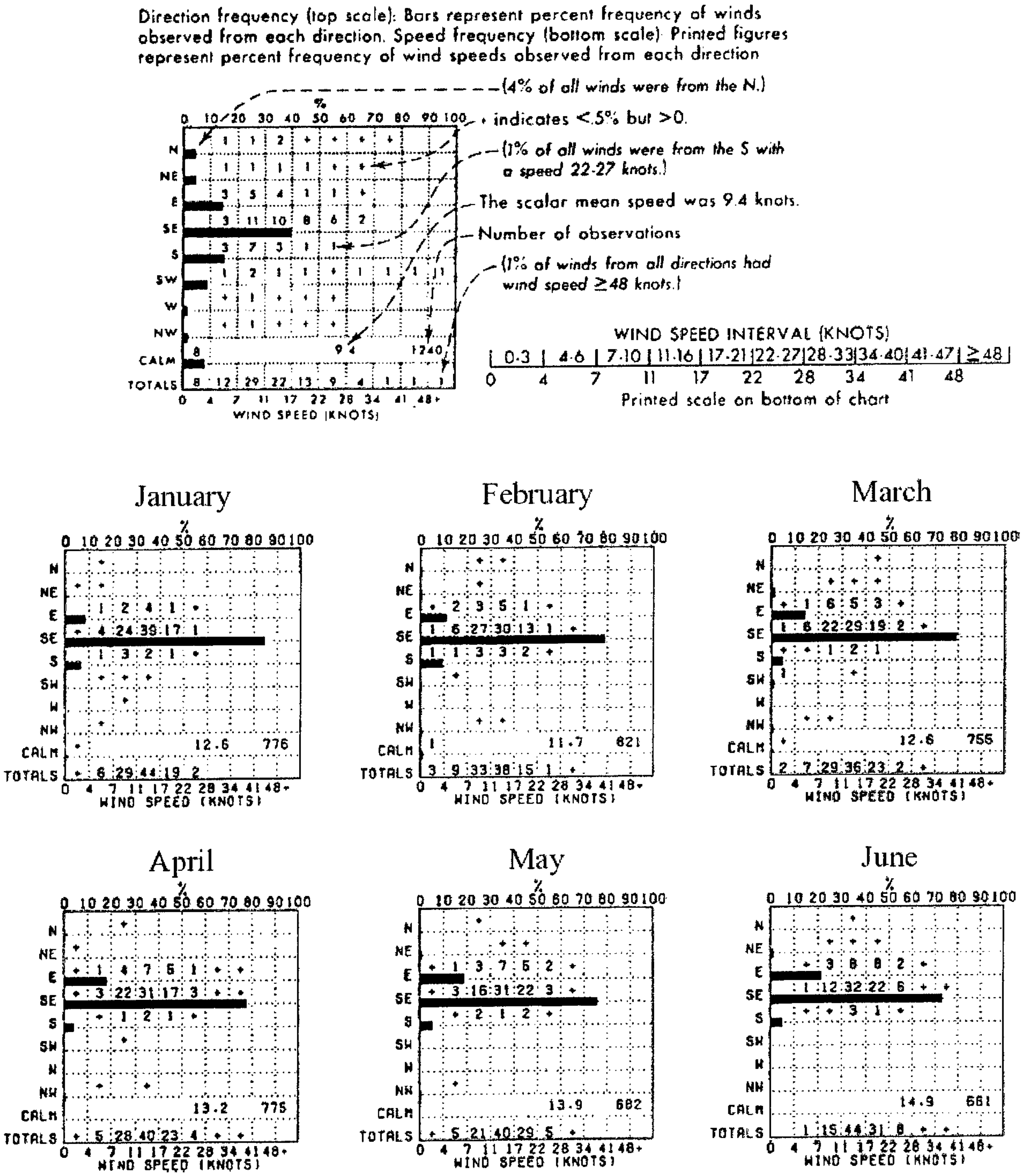


Figure 3-3. Ascension is subject to strong prevailing winds (~ 25 to 32 km/hr) from the SSE, data were taken from World Survey of Climatology Vol 15, Climates of the Oceans, ed. H. Van Loon, Elsevier, 1984.

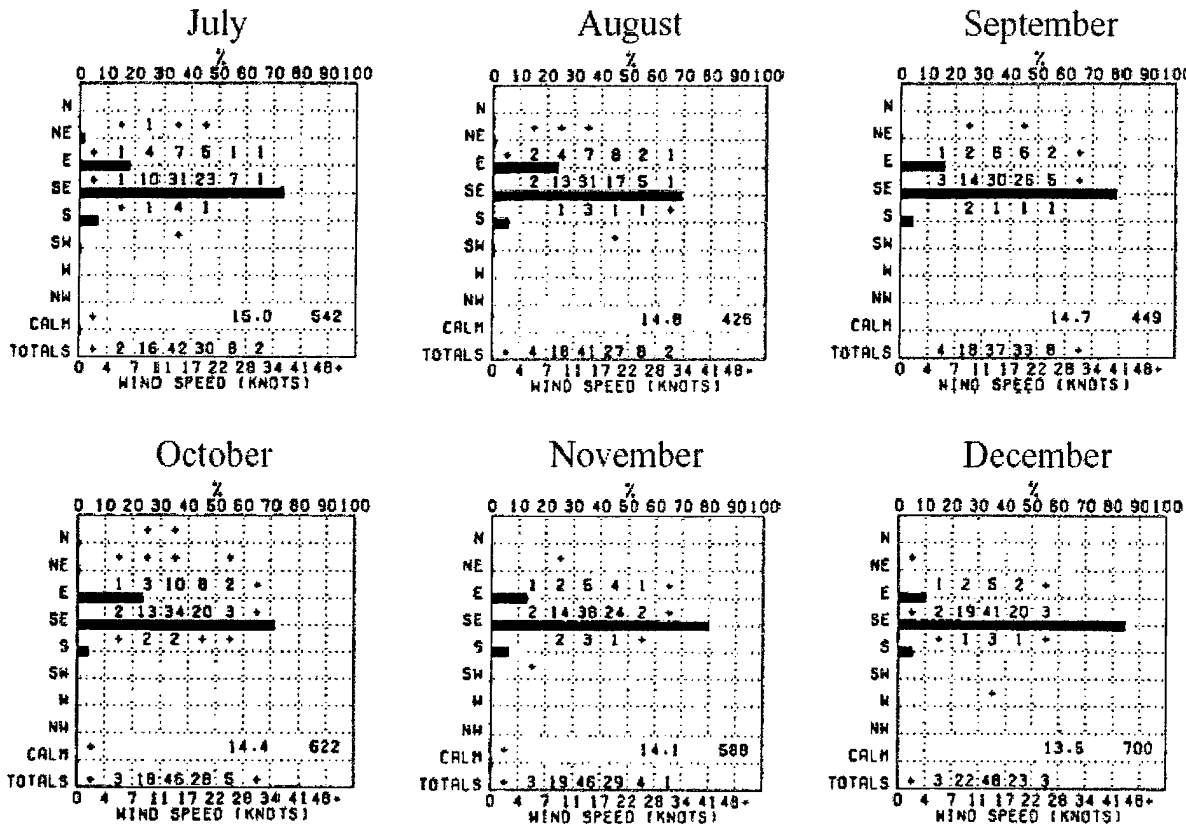


Figure 3-3. (continued) Ascension is subject to strong prevaling winds (~ 25 to 32 km/hr) from the SSE. These data were taken from World Survey of Climatology Vol 15, Climates of the Oceans, ed. H. Van Loon, Elsevier, 1984.

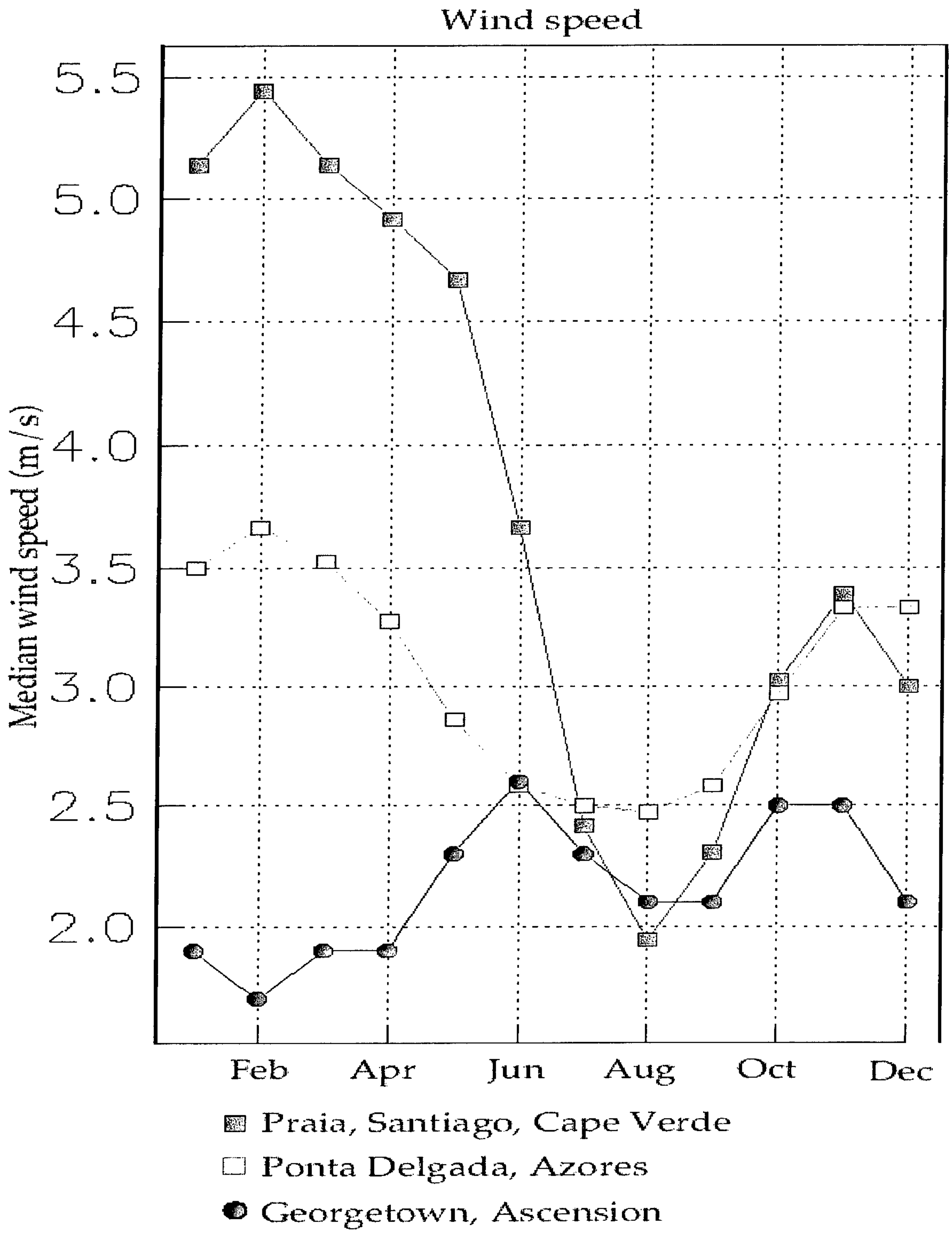


Figure 3-4. Long-term wind speed at Georgetown relative to wind speeds observed at sites in Cape Verde and the Azores. Georgetown is shielded from strong tradewinds by Green Mountain to the southeast.

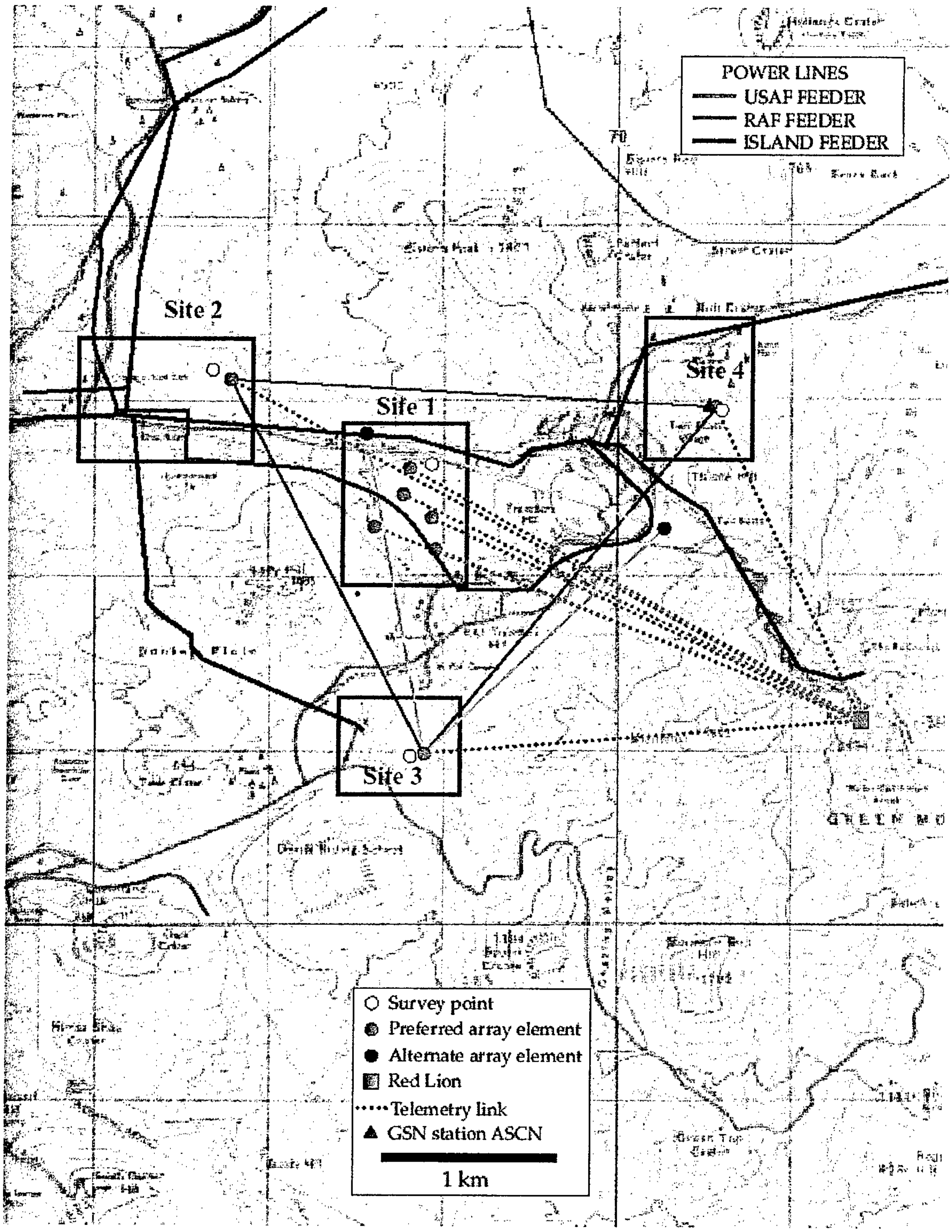


Figure 3-5. Topography and infrastructure near the center of Ascension island with survey sites indicated by the yellow symbols, the recommended IMS array indicated by the green symbols and the red triangle and all space filters with the exception of the 18 m filters proposed for the central mini-array plotted to scale. The array site 7 is located just east of the Global Seismographic Network station ASCN with an alternate array design shown in pale green (with black and green symbols) and the boxes indicating the areas shown in figures 3-12 through 3-15, with the box in 3-2 showing the portion of the island covered by this figure.

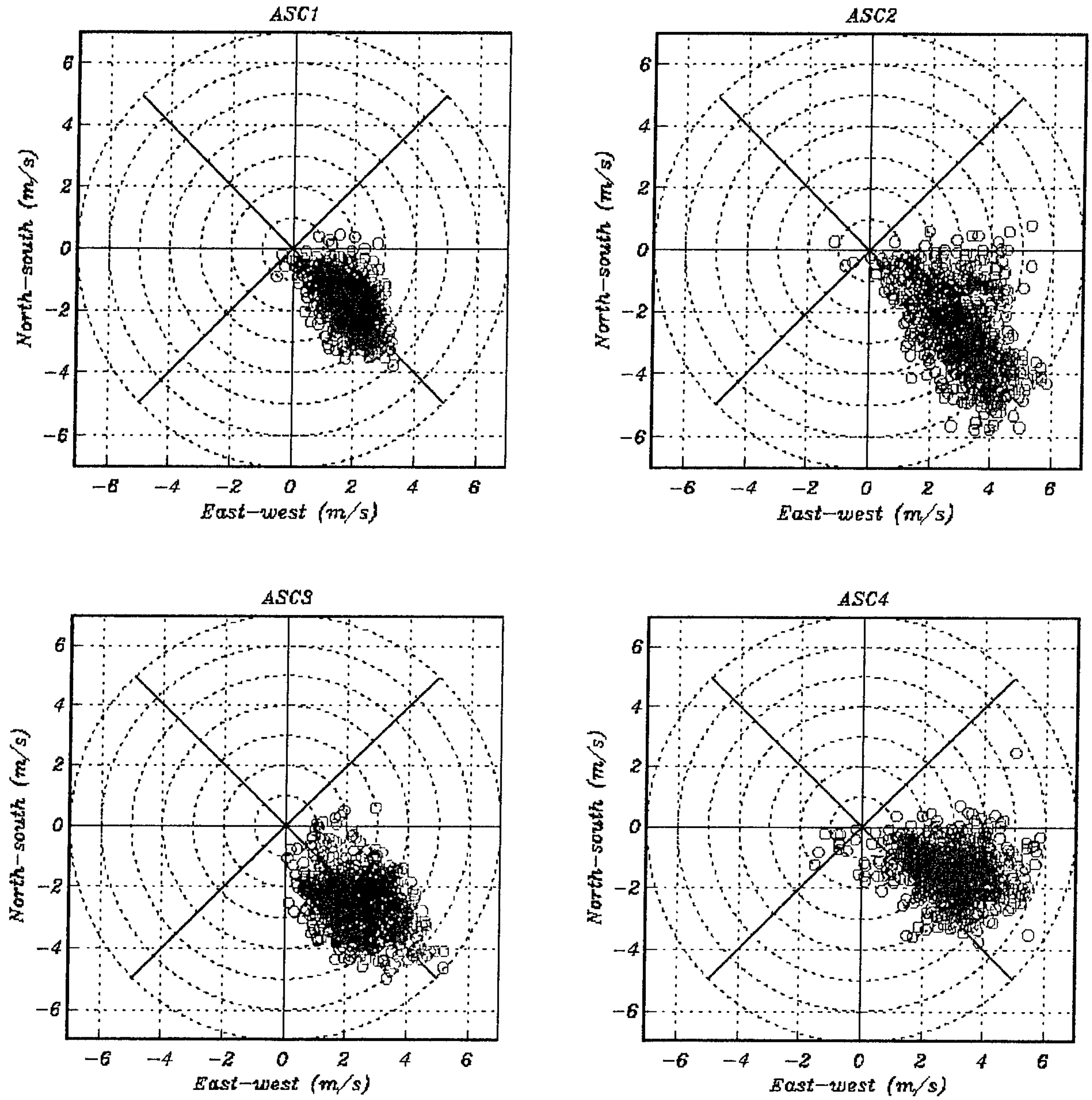


Figure 3-6. wind velocity at the four sties with local winds are dominated by the SE trades.

wind speed at this site during our survey was 2.55 m/s. The average wind speeds at the other sites ranged from 3.33 to 4.02 m/s.

3.8 POWER SPECTRAL ANALYSIS METHOD.

All field data were downloaded from the Reftek disks and placed in CSS3.0 format databases. To examine the spectral content of the filtered data we used Welch's method (Welch, 1967) which yields a single power spectral estimate from an average of several taken at regular intervals in the time range of interest. The spectral estimates we have used in this study were derived from an average of 4 estimates,

each taken from consecutive 204.8 s intervals. The power spectral estimates were obtained using the Matlab routine "PSD".

3.9 NOISE LEVELS AT THE SURVEY SITES.

Fifteen minutes of pressure and meteorological data from the Ascension experiment are shown in Figure 3-7. The unfiltered pressure time-series from the station at site 1 exhibits 30 s period fluctuations superimposed on substantially longer period energy. The shorter period variations dominate the filtered record (second panel). In this time period, minor wind velocity fluctuations are constant. The temperature and humidity vary relatively slowly. The detailed structure of the filtered pressure record results from the superposed contributions of myriad atmospheric phenomena. Our study is concerned primarily with the dependence of the noise on frequency and the exact location of the sensor and thus we will focus on the spectral properties of the noise.

The power spectral density taken from the filtered record (Figure 3-8) shows a decay in power levels from the peak at 30 s to the corner of the anti-aliasing filter at 9 Hz. The microbarom peak was not seen in this time interval.

From the full 5 weeks of recording at all 4 sites we calculated power spectral denstiy at 705 time intervals. Each interval began at the turning of the hour and lasted for 15 minutes (such as the interval displayed in Figure 3-7). Tenth, 50th and 90 percentile noise levels at all frequencies from 0.005 Hz to 10.0 Hz are shown in Figure 3-8 with the minimum and maximum power levels. At times of relatively low noise the microbarom peak is obvious at Site 1. This figure shows that the interval displayed in Figure 3-7 was a time of near-average noise levels.

The same spectral character is seen at all four sites (Figure 3-9). The microbarom, which is clearly seen at times of low infrasonic noise, is usually not observed at any of the sites. With the exception of elevated high-frequency noise levels seen in one time interval at Sites 2 and 3, the noise levels at the four sites are very similar.

Infrasonic noise levels at Ascension island are compared with those observed at 4 other IMS infrasound array locations in Figure 1-9. Median noise levels at Ascension are ~10 dB higher than median noise levels observed at the Pinon Flat Observatory in California. Median noise levels at Ascension are comparable to those observed in the Azores and Cape Verde. The minimum noise level observed at Ascension island is also comparable to the noise levels observed at the other sites in the Atlantic. The maximum noise levels are ~ 10 dB lower than those observed in the Azores.

As expected, the noise power in the band between .005 Hz and 10 Hz is highly dependent on wind speed. In Figure 3-10 we display the power spectral density at several frequencies between .02 and 5 Hz as a function of wind speed. At times of weak winds the infrasonic noise levels are quite low. Minimum power density levels of ~2x10-6 Pa2/Hz are seen at 5 Hz. Infrasonic power levels at long periods (20 s) varied by 40 dB during the experiment. The wind speeds depend strongly on the site. Wind speeds are clearly reduced in the sparse forest at site 1 however there is no obvious reduction in infrasonic noise levels at periods of 1 s and longer. We see a noise reduction of ~ 5 dB at frequencies above 1 Hz during peak wind conditions.

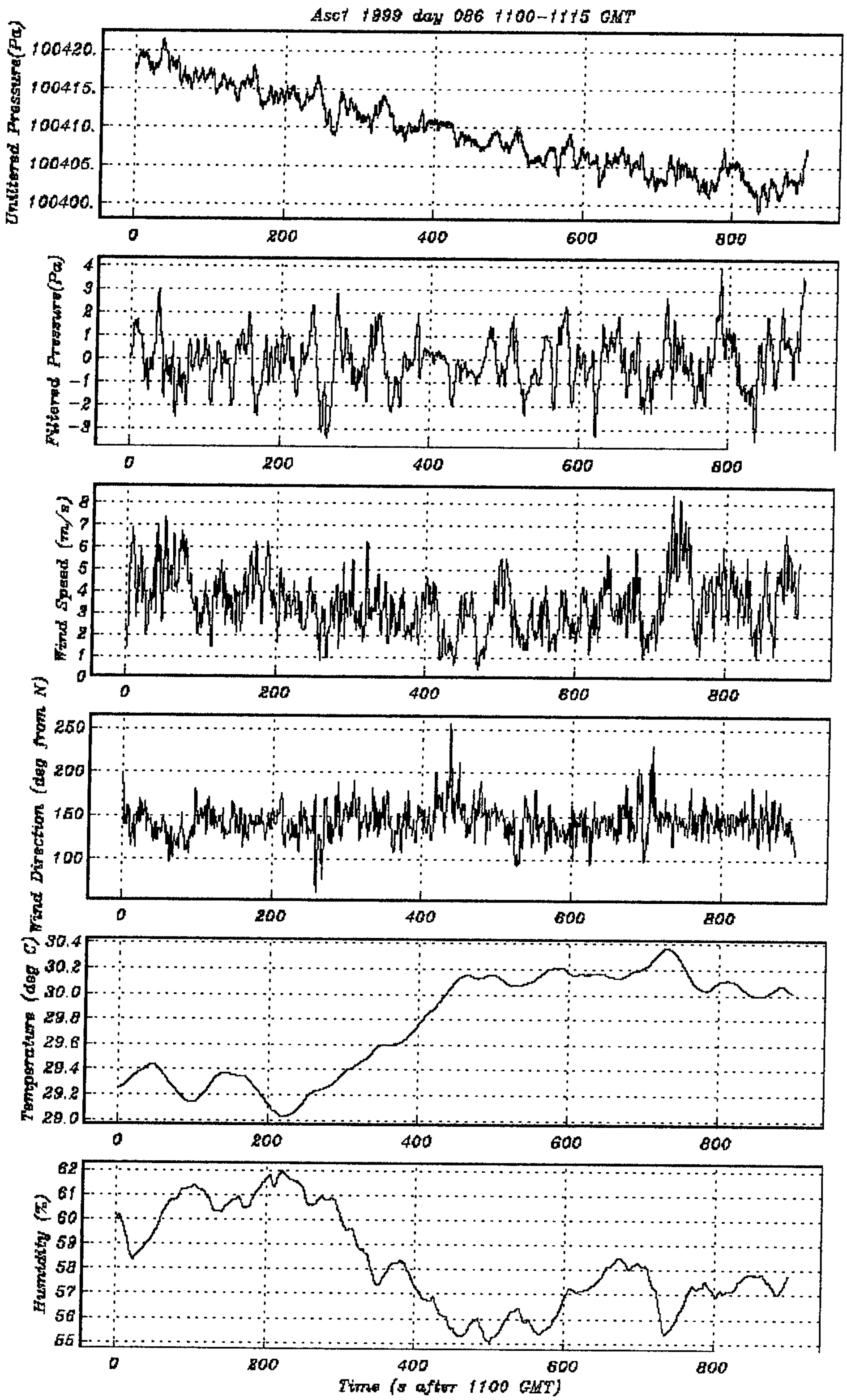


Figure 3-7. Atmospheric pressure and meteorological data during a 15 minute interval on day 86, 1999, with raw and filtered pressure data shown in the upper two panels, and wind speed, direction, temperature and humidity shown below.

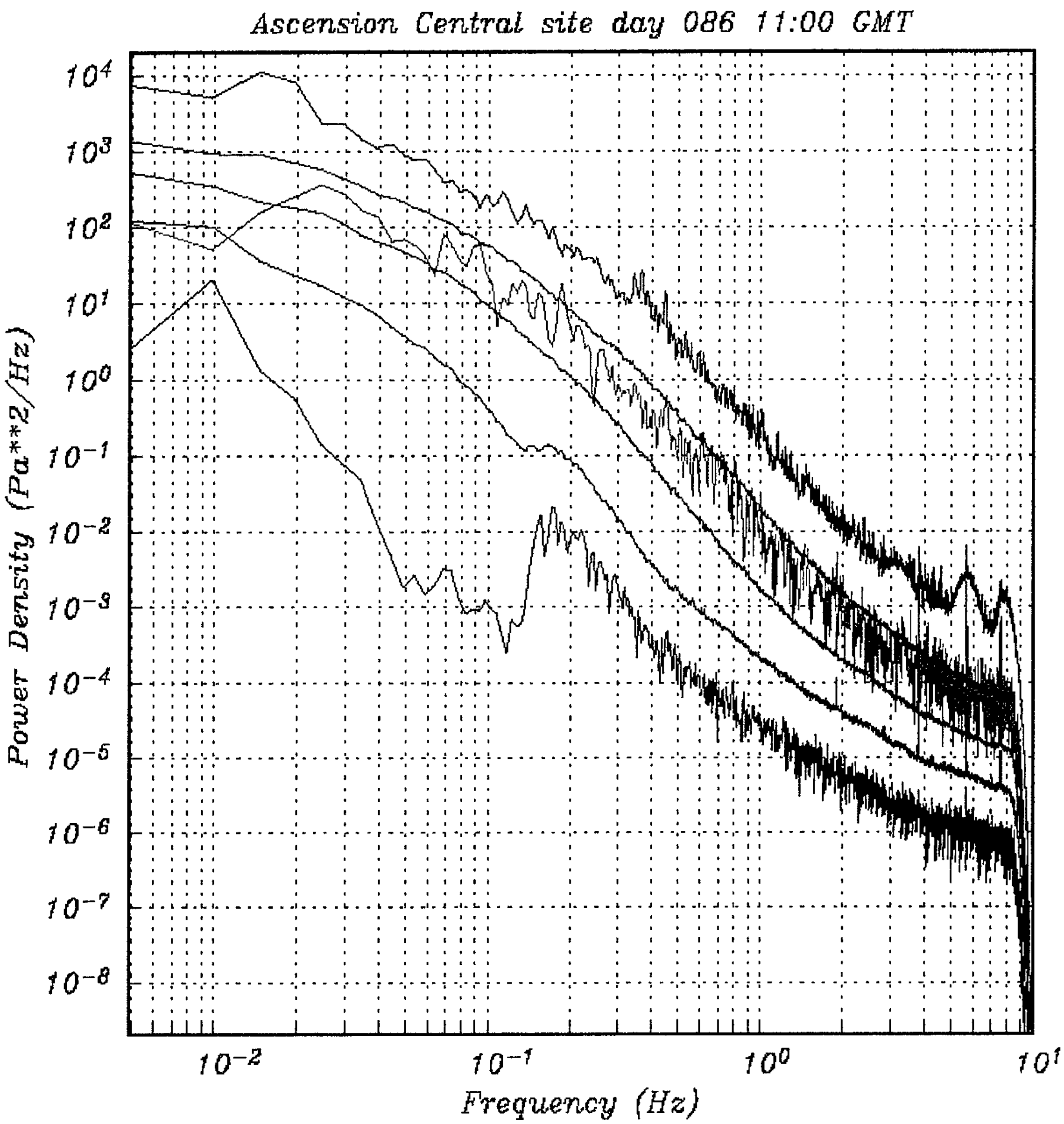


Figure 3-8. A time averaged (Welch) spectrum (in red) and minimum, 10th, 50th and 90th percentile and maximum noise curves from Site 1, with the lowest and uppermost curves being the minimum and maximum noise levels observed at this site during the 3 weeks of the experiment and each estimate taken from 15 minutes of data.

3.10 TEMPORAL VARIATIONS IN NOISE LEVELS.

We observed significant changes in wind speed and noise levels during our three-week experiment. The experiment in early 1999 included no significant storms (Figure 3-11).

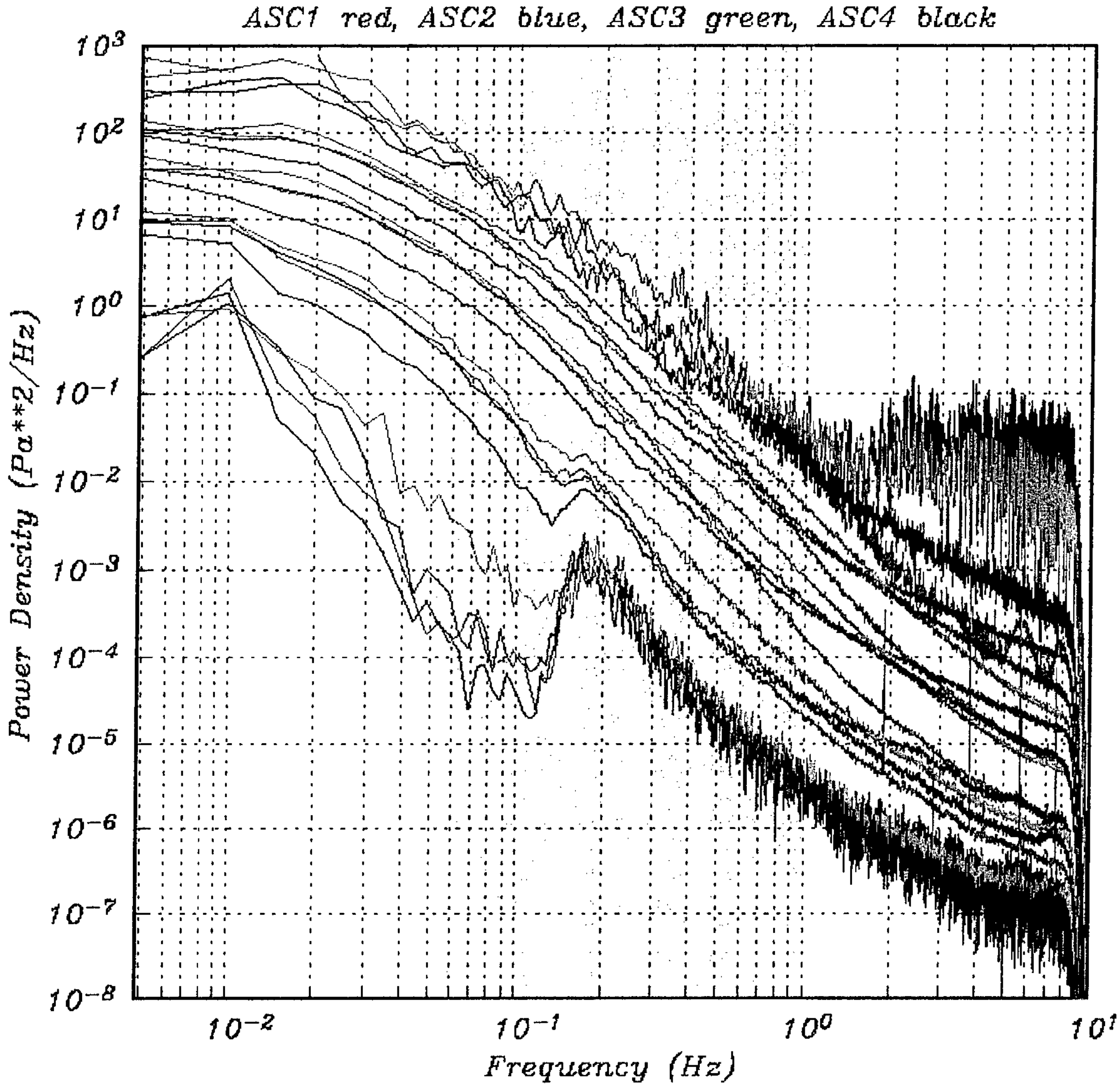


Figure 3-9. The three inner curves are the 10th, 50th and 90th percentile noise levels at the 4 sites and the lower and upper curves are the minimum and maximum noise levels respectively at the 4 sites during the 3 week experiment, with the band of greatest interest to the monitoring community shaded.

3.11 CONCLUSIONS AND RECOMMENDATIONS.

The principal conclusions of this report are the location and the configuration of the infrasound array we are recommending for Ascension Island. These points are discussed in Sections 5.1, 5.3 and 5.4. We discuss the validity of the survey results in Section 5.2. In Sections 5.5 through 5.11 we discuss the expected performance of this array and the logistics of establishing and maintaining the infrasound array.

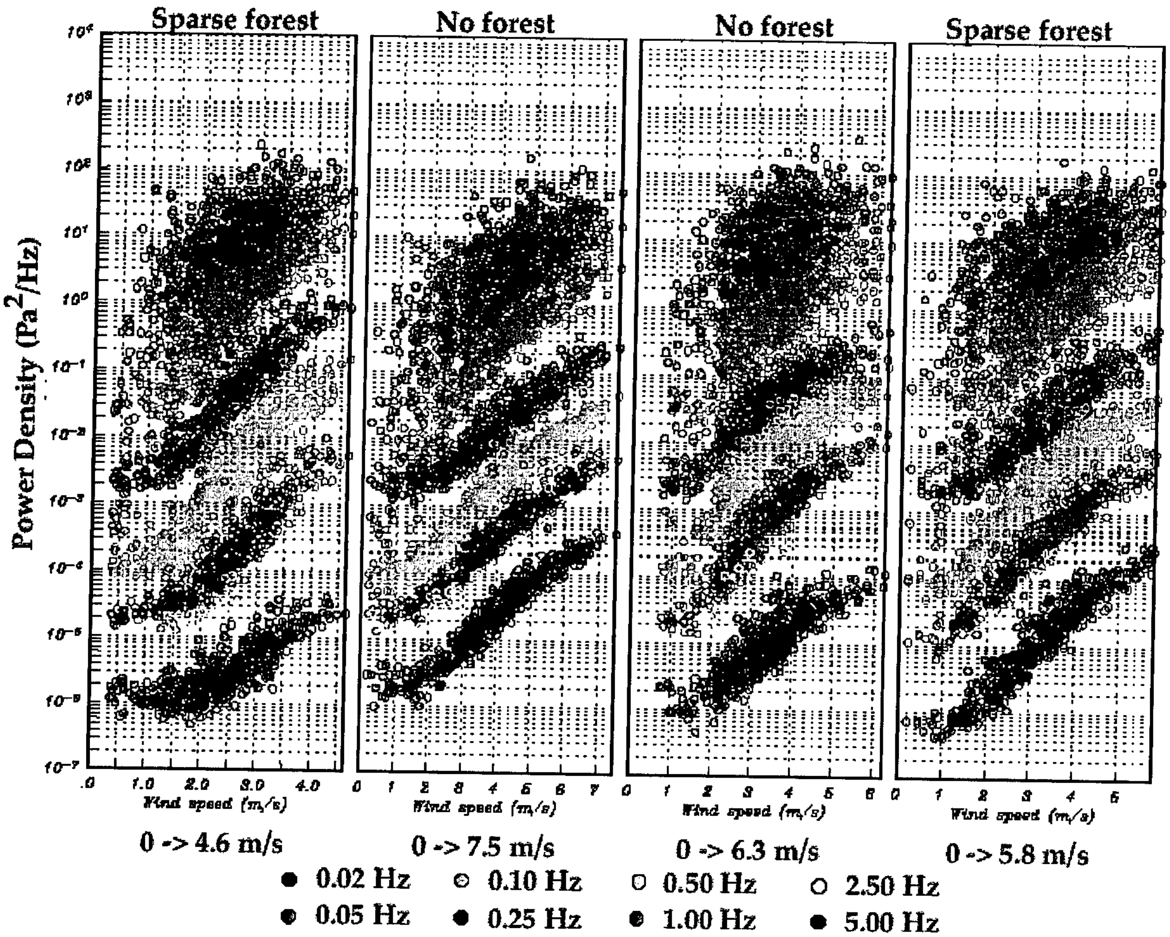


Figure 3-10. Dependence of infrasonic noise on wind speed and frequency at the four sites on Ascension Island, with, from top to bottom in each panel, noise power at 0.02 Hz (black); 0.05 Hz (red); 0.1 Hz (green); 0.25 Hz (dark blue); 0.5 Hz (light blue); 1.0 Hz (pink); 2.5 Hz (yellow); and 5.0 Hz (black).

3.11.1 Determination of the most suitable site.

The primary objective of this field program is to identify the location near the nominal coordinates of IS50 that is most suitable for a permanent IMS infrasound array. The paramount factor is infrasonic noise however our selection must be guided by practical considerations. A site that offers low infrasonic noise but gives few options for siting a permanent array might not be optimal. The ideal site is large enough to allow any array configuration from 1 to 3 km aperture to be considered. On Ascension Island, the only area that can accommodate an infrasound array of these dimensions is near the center of the island.

A careful review of meteorological data collected at several sites in the vicinity of Ascension Island indicates that wind speeds at all areas can be expected to be high, on average. The data analysis indicates that the kind of vegetation commonly found on Ascension island will reduce wind speeds by up to 30% however infrasonic noise levels below 1 s are not depressed substantially.

Having considered the meteorological and infrasound data, and having considered the points listed in Section 3.3, we have concluded that the best option for the IMS infrasound array IS50 is near Travelers Hill at the center of the island.

Our survey indicates that all sites near the middle of Ascension Island have comparable noise levels. This area is relatively flat (when compared to other sites on the island) but gives few options for array design. Our brief survey indicates that this area is subject to substantial noise level swings (Figure 3-11) however comparable noise swings can be expected at other nearby sites. Any infrasound monitoring station located in the region will offer a highly variable performance - particularly during the winter when storms are not uncommon. As shown in Figure 3-4, our survey was conducted at a time of near-average winds.

3.11.2 Validity of Survey Results.

Because of limited resources and manpower, this infrasound site survey lasted 68 days. Simultaneous recording at all 4 sites occurred over a 33 day time span. This gives just a glimpse of the full range of meteorological conditions that will occur in a typical year. Is it fair to assume that the brief period sampled is representative of the entire year and the survey will allow us to recommend the best site or is a 2 to 3 week survey too brief to be useful? For a brief survey to be ineffective, climactic conditions at the time of the survey would have to be out of the ordinary and tilt the balance of infrasonic noise so that the relative noise levels at the sites are not representative of the yearly average. Intuitively, this seems rather unlikely and easy to check. The chief source of infrasonic noise is turbulence due to wind flow over topography. If wind direction changes in such a way that the wind-topography interaction at the time of the survey is unusual and, as a result, anomalously little turbulance is generated at certain sites, or excessive turbulence is generated at others, the brief survey taken at that time would be misleading. It should be possible to rule out this scenario by comparing wind velocity measurements made during the survey with those from long-term meteorological observations. A significant discrepancy in wind speed or direction combined with azimuthally dependent topography would be cause for concern. The winds observed during the survey appear to be consistent with long-term observations.

3.11.3 Proposed Permanent Array Configuration.

The surveys are to consider infrasound arrays with apertures between 1 and 3 km. Large arrays permit more accurate estimates of the back azimuth of infrasound sources but require highly coherent signals. Smaller arrays have poorer resolution however are preferred at locations where signal coherence is poor. At sites where noise, most notably the microbarom, is highly coherent, larger offsets between array elements might be required. Due to constraints presented by topography we are recommending an array with an aperture of ~ 2.5 km. Although the standard IMS array is to include just 4 sensors, we believe that the ambient wind conditions and overall noise levels in the region are high enough so that adequate array performance will require an augmented array of 8 elements. The preferred array is depicted in Figure 3-5. This array includes 5 elements in a central area ~ 300 m across.

GPS coordinates of the array sites and the Red Lion processing facility (CPF) are given in Table 3-1. Sites 1 through 4 are in the inner, high-frequency optimized, array. Sites 5,6 and 7 are in the outer, long-period, array. We propose both short-period and long-period elements at Site 1.

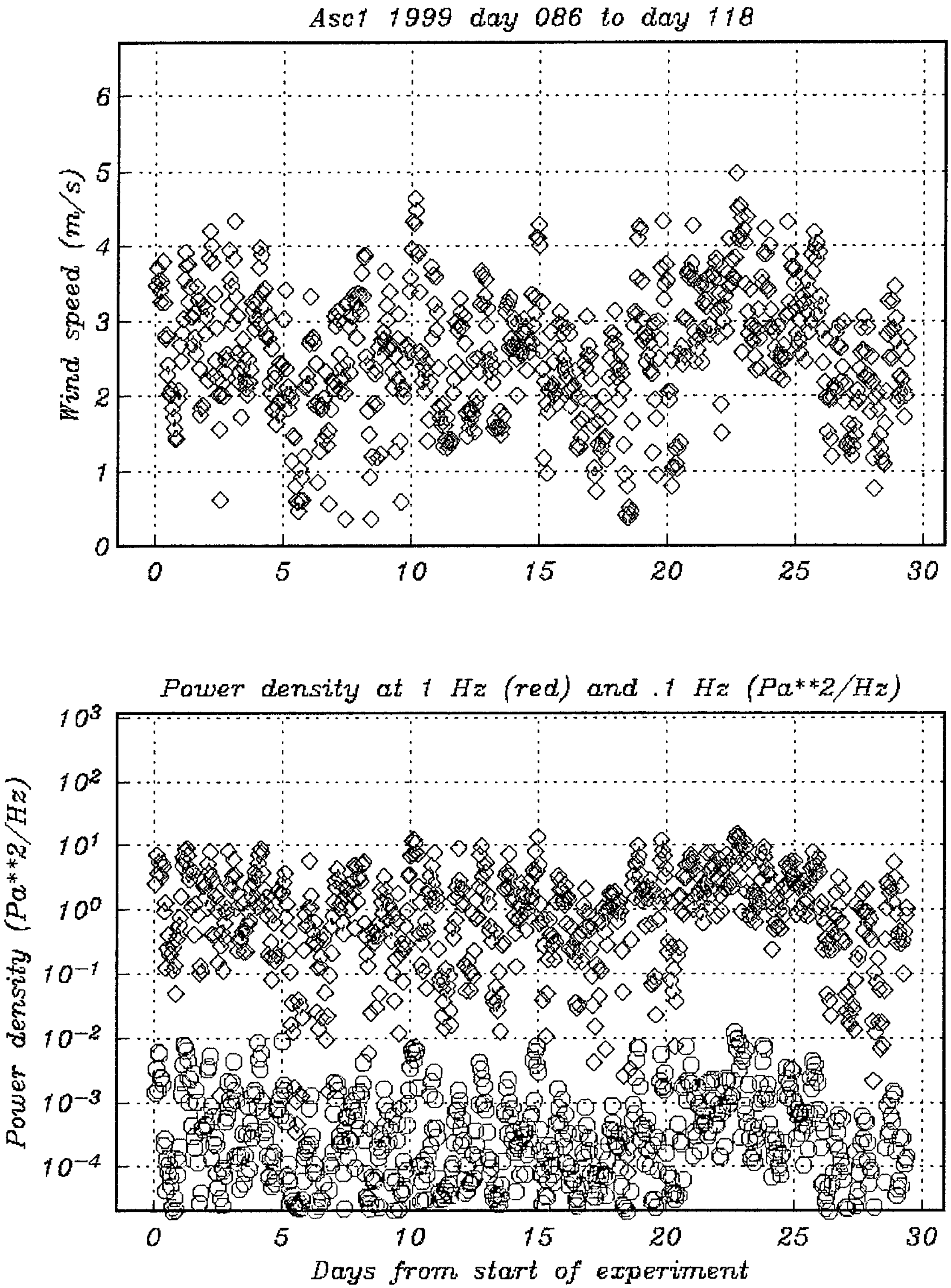


Figure 3-11. Noise power and wind speed as a function of time at station 1, with wind noise at 0.1 Hz (upper sequence of points in the lower panel) and at 1.0 Hz tracking closely the wind speed with non instantaneous but are average wind speeds during a 15 minute interval during which the noise power was estimated .

Table 3-1: Coordinates of elements in proposed array

	Latitude (°S)	**Longitude (°W)**	**Elevation (m)**
Site 1.	7° 56.26′	14° 22.51′	165
Site 2.	7° 56.36′	14° 22.60′	162
Site 3.	7° 56.43′	14° 22.41′	180
Site 4.	7° 56.18′	14° 22.49′	168
Site 5.	7° 55.91′	14° 23.05′	122
Site 6.	7° 57.06′	14° 22.44′	168
Site 7.	7° 55.99′	14° 21.53′	198
CPF	7° 57.00′	14° 21.13′	671
GCI VSAT	7° 57.00′	14° 21.13′	671

All of these sites are located on British Crown land. Photos and detailed drawings of these sites are shown in Figures 3-12 through 3-15.

Signal blockage in this area is not a significant issue. Likewise, turbulence from air flow off nearby topography should not be a serious consideration. With the exception of some horizon blockage caused by small nearby hills (most notably Green Mountain), all topography lies below 10°above the horizontal. Most sites see to within 5°of the horizon at virtually all azimuths. The most significant horizon loss exists at the site in Butt crater.

3.11.4 Array response.

The impulse response of the recommended array configuration is shown in Figure 3-16. In this figure, we display the amplitude of the array response at a linear scale. All values are normalized to 1 at the peak of the mainlobe. The impulse reponse has been calculated at wavenumbers between +/- 1.5 cycles/km. These wavenumber limits include acoustic energy at wavenumbers down to that of a 0.5 Hz horizontally propagating wave. The impulse response has several sidelobes at wavenumbers between 0.75 and 1.0 cycles/km. The sidelobes peak at ~70% the amplitude of the mainlobe. The dominance of the mainlobe in this array response calculation is largely due to the addition of extra elements near the center of the array.

3.11.5 Wind-noise reducing space filters.

Following the recommendations of the PTS, we believe the most suitable noise filters for this location are the multiport filters discussed in Appendix A. We recommend 70 m aperture noise filters for all outer elements in the array. This should enhance the effectiveness of the outer array for detecting long period (20 s to 1 Hz) signals. We recommend that the stations in the inner 300 aperture mini-array be equipped with 18 m aperture space filters to improve detection of high-frequency (1 to 4 Hz) signals with one site (Site 1) also equipped with a 70 m filter.

3.11.6 Central recording facility.

We recommend that the central recording facility be located at Red Lion facility on Green Mountain (Figure 3-8). The GCI VSAT antenna should be placed beside the facility.

3.11.7 Communications.

We tentatively recommend telemetered communications at this array between the elements and the central processing facility at Red Lion. Ascension is the site of a considerable array of broadcasting equipment. All requests for additional broadcasting infrastructure must go through the Administrator and will be reviewed by representatives of several organizations on the island. Approval will depend on the frequency and power level requested, international standards and local usage by various groups (include the police, the marine, civil, military, television). The island conforms to International Tellecomunications Union (ITU) standards. Iain Atkinson is the resident engineer with Merlin Communications on Ascension Island. Merlin is a commercial offshoot of the BBC. Merlin operates a facility

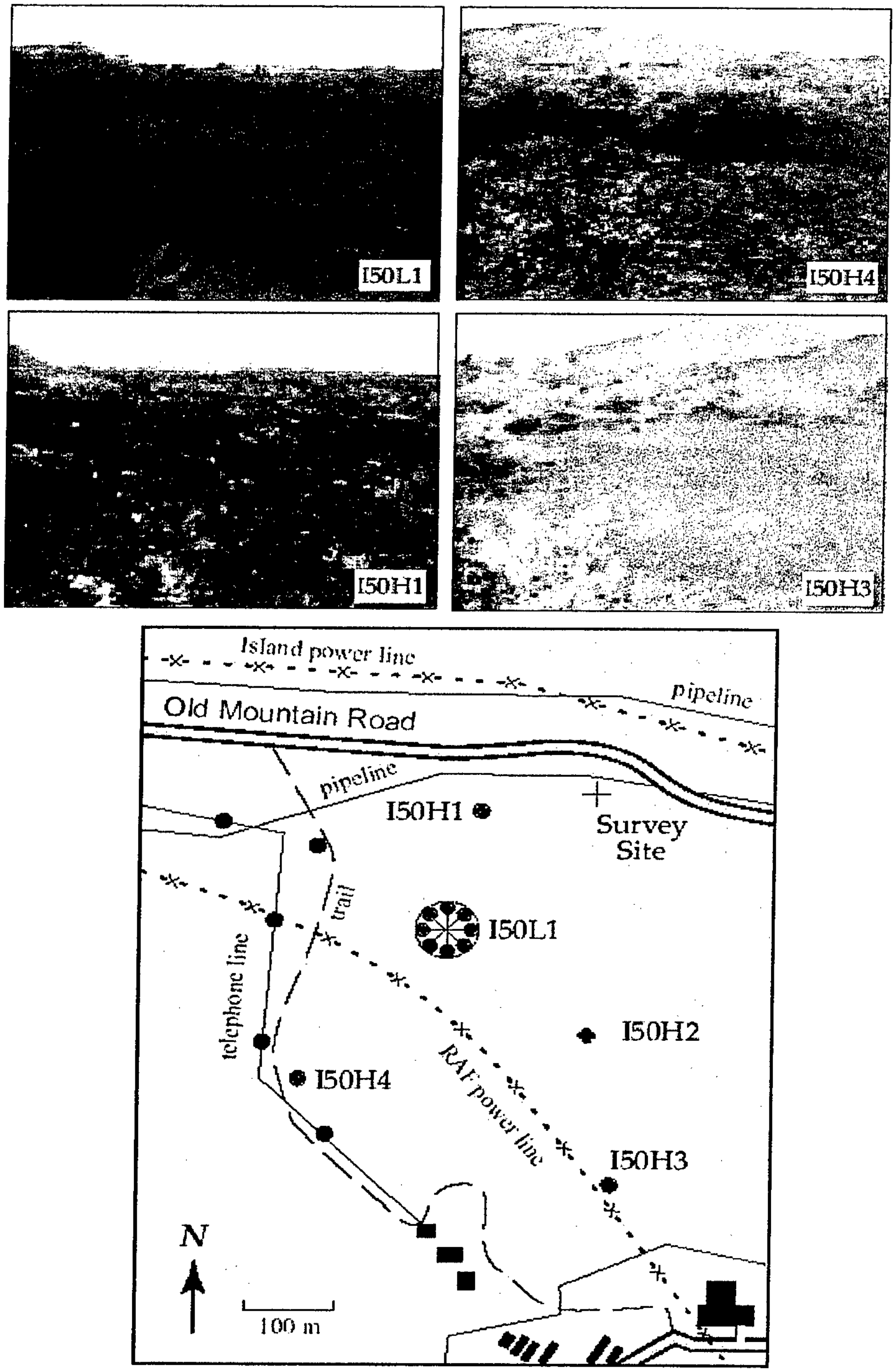
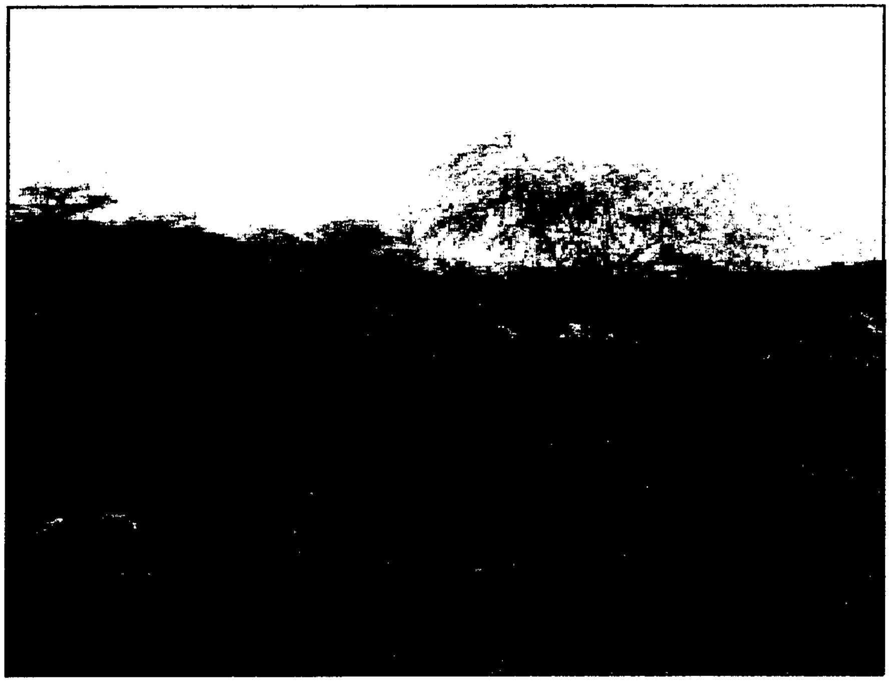


Figure 3-12. Photos and sketch of the central area of the proposed array with single photos of each array element shown in the upper half of the figure and a plan view of the (Figure 2-2).



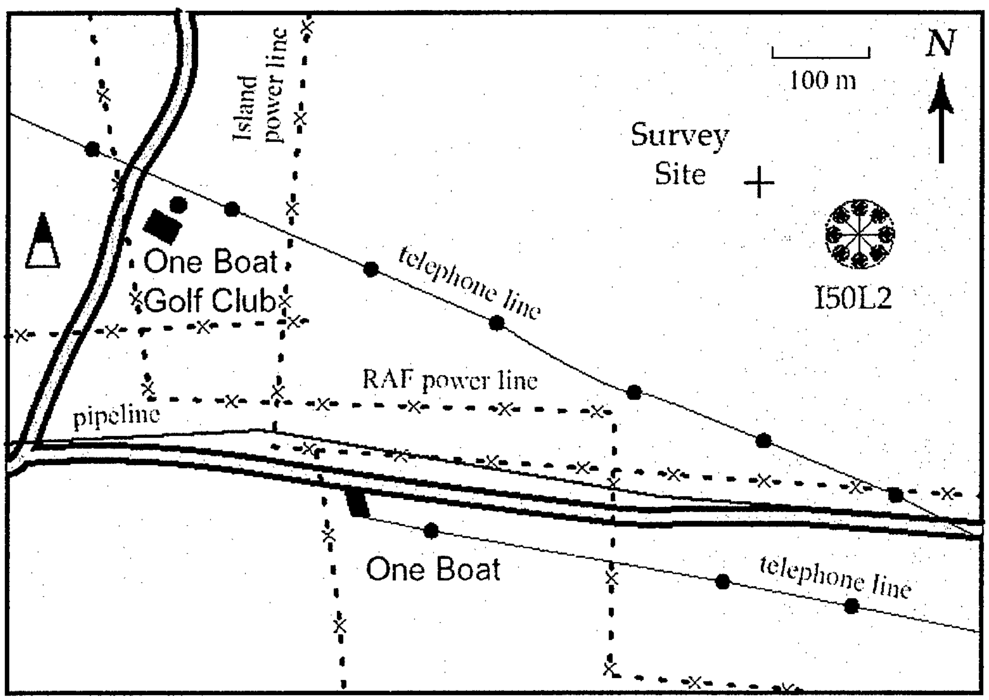


Figure 3-13. Photo and sketch of the northwest site in the proposed array.

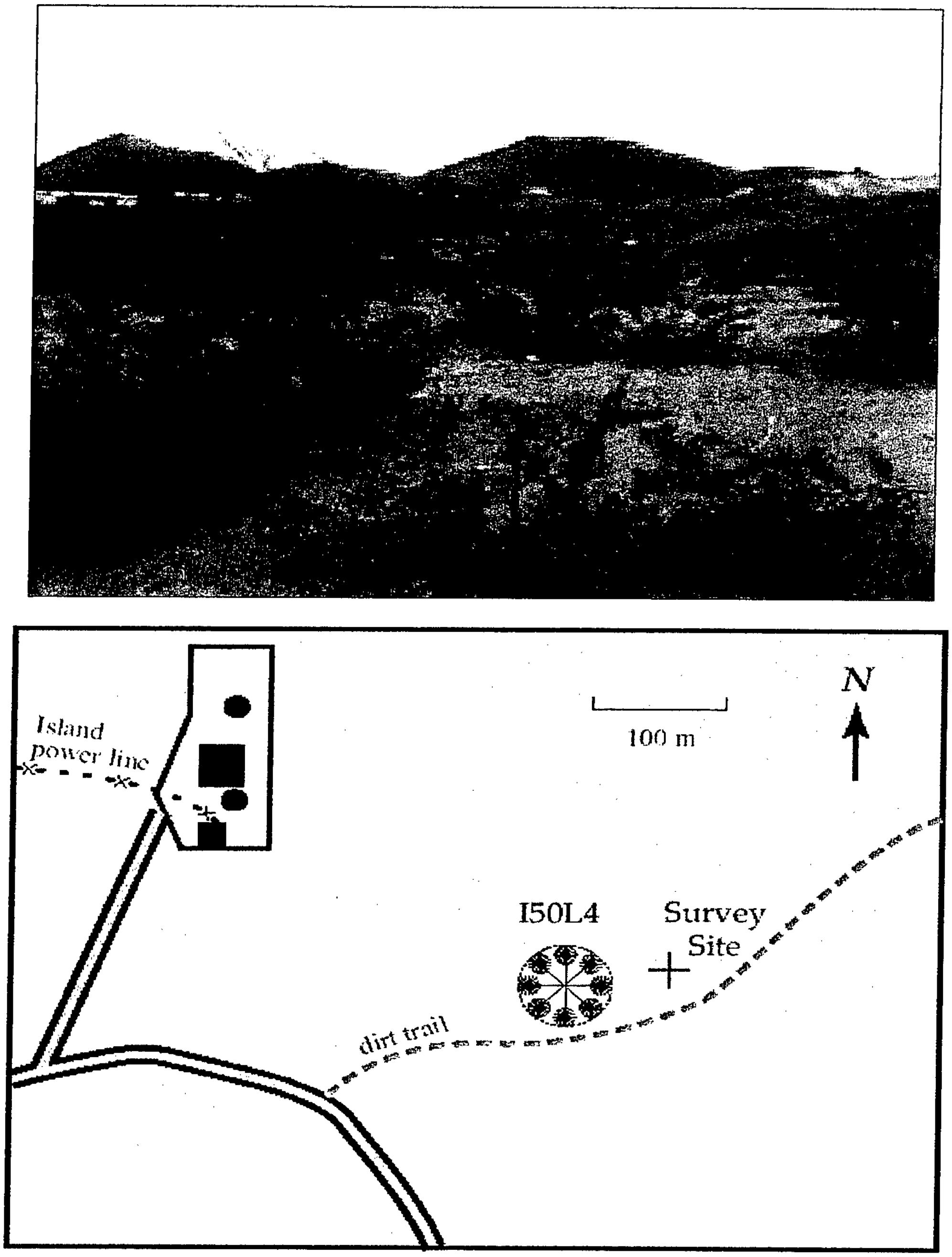
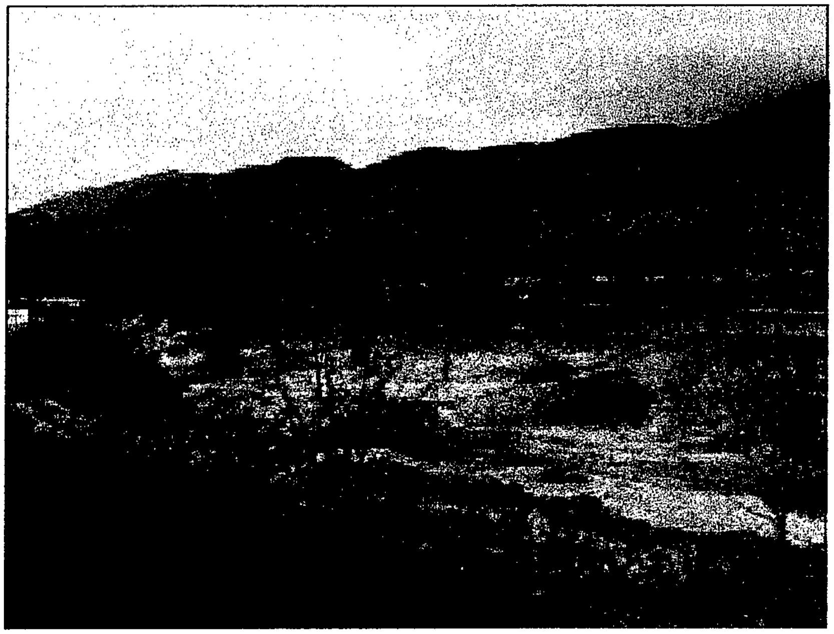


Figure 3-14. Photo and sketch of the southern site in the proposed array.

above "Red Lion" on the NW slope of Green mountain. Merlin's facility (Bells Cottage) has radio repeaters for the police and ambulance. There is room for additional equipment. Space at Bells Cottage can be rented from Merlin.

Iain Atkinson has indicated that Merlin would be willing to serve as a technical contact. Merlin is highly experienced with transmission issues.



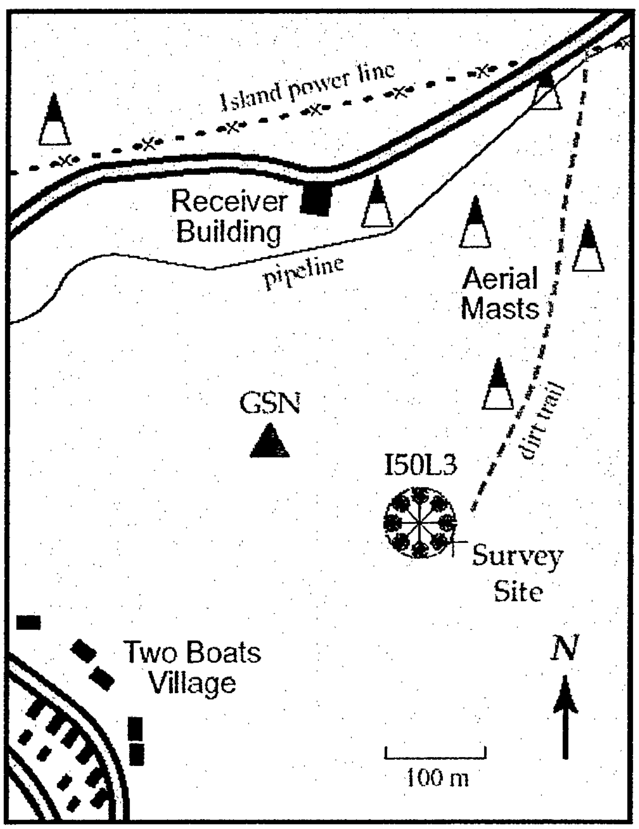


Figure 3-15. Photo and sketch of the eastern site in the proposed array located adjacent to the Global Seismographic Network station ASCN.

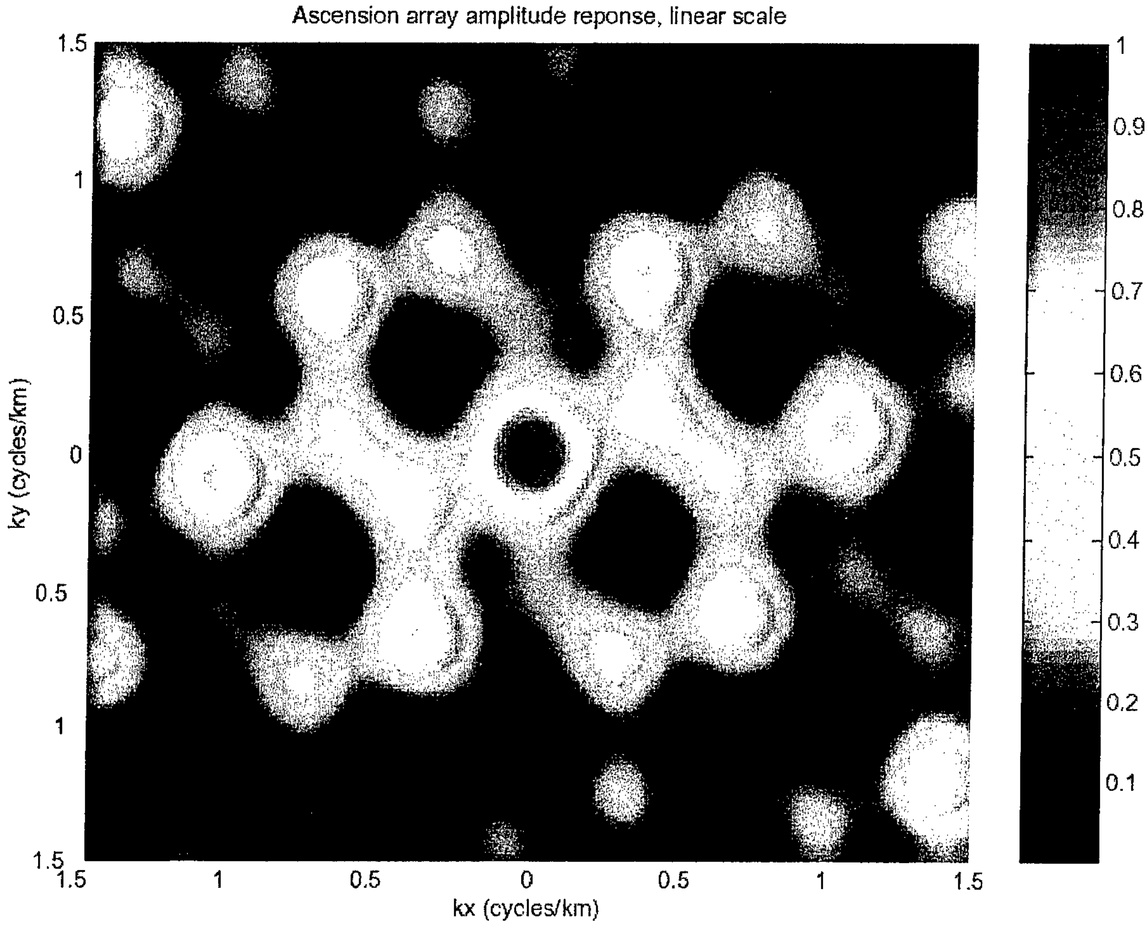


Figure 3-16. Impulse response of the recommended 8 element array on Ascension island.

3.11.8 Power.

There are two existing power systems on the island. The UK power station is at English bay at the northwest corner of the island. The lines carry 11 kV. This facility is run by Merlin communications. The USAF power system powers the USAF base and extends to Comfortless cove and Cross hill.

3.11.9 Land Tenure and access.

All land on the island is British Crown land. Long term usage of the land will incur a "black box" fee. The amount of the fee is not yet known but can be provided by the Administrator upon request.

3.11.10 Security.

Security concerns are omnipresent however there is no reason to suspect this is more of a concern at this location than at any of the other stations in the global network. This is in part because there is no where to take stolen items. The people of Ascension Island are arguably the friendliest in the world.

3.11.11 Protection from natural hazards and animals.

This site is subject to three natural hazards. Floods, volcanic eruptions (last one 600 years ago) and animals - most notably donkeys. All sites in the recommended array are located at points we believe that are not subject to flooding. We recommend erecting a chain link fence around all the equipment for protection from the wildlife.

SECTION 4
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APPENDIX A
RECOMMENDED SPACE FILTERS FOR THE AZORES, CAPE VERDE AND ASCENSION ISLAND

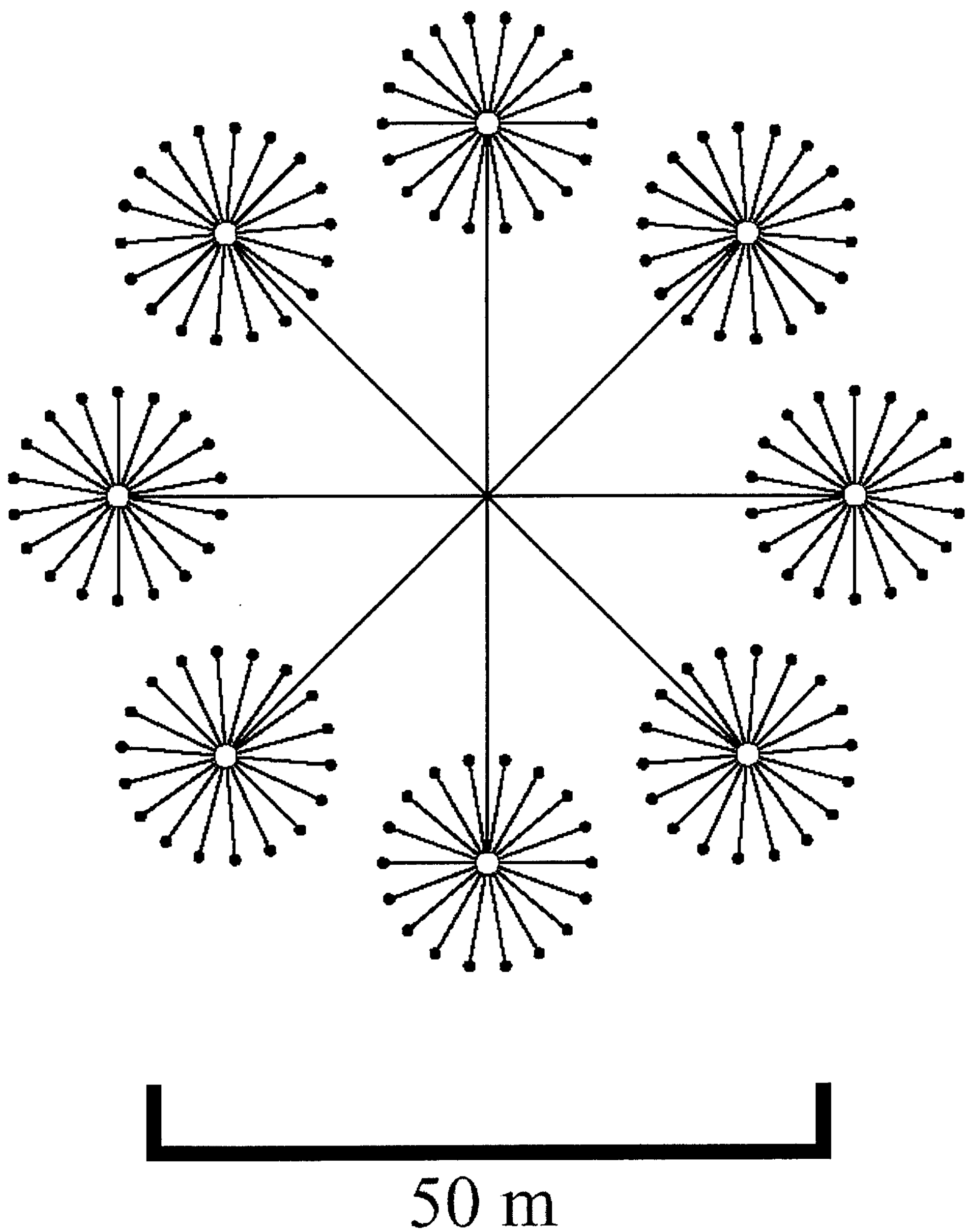

Figure A-1. 144-port 70m diameter wind-noise-reducing pipe array with low-frequency capability for use at long-period-optimized array elements at stations located in higher wind areas.

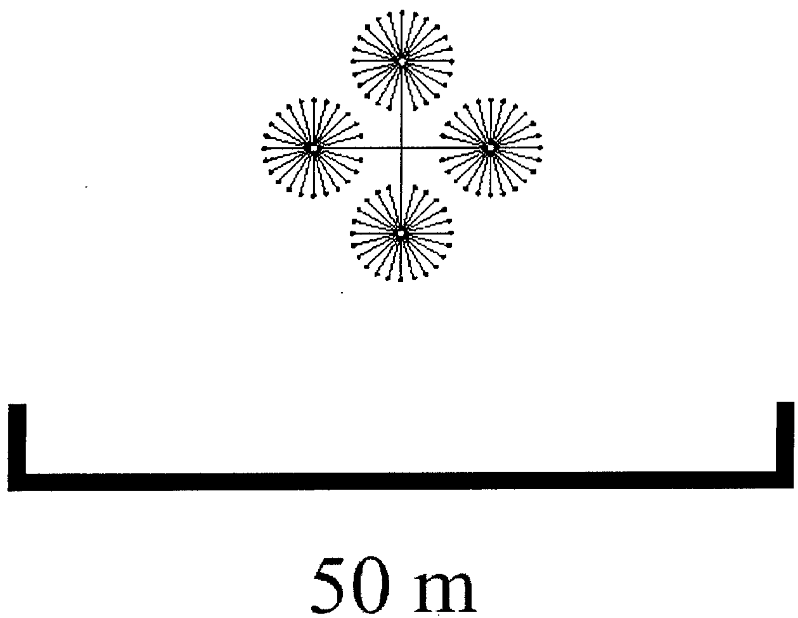

Figure A-2. 92-port 18m diameter wind-noise-reducing pipe array with high-frequency capability for use at short-period-optimized array elements at stations located in high wind areas or at all array elements at stations located in low wind areas.

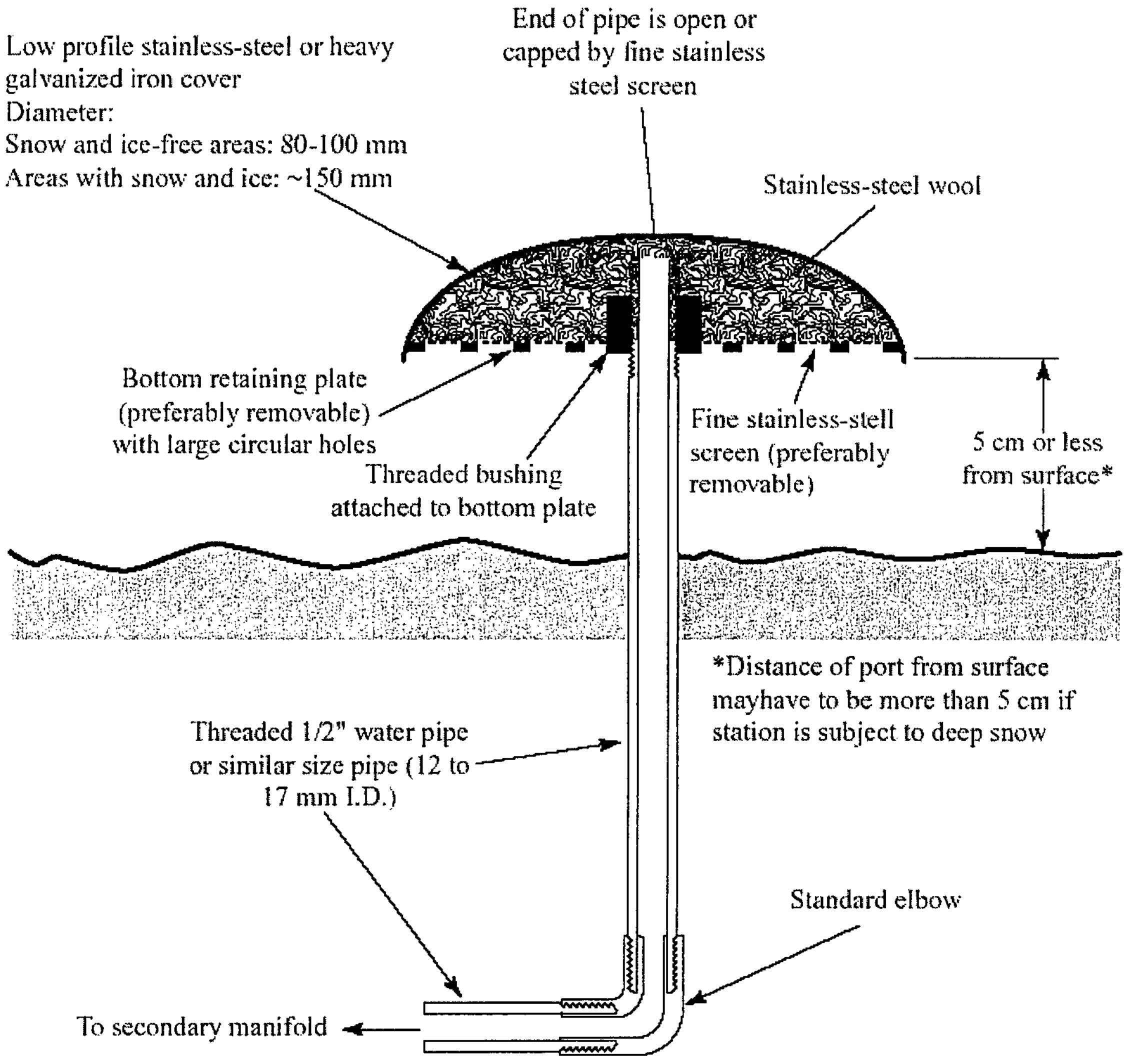

Figure A-3. Cross section of a single port attached to a buried pipe system, drawing and labels courtesy of Doug Christie (PTSCTBTO).

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